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TECHNICAL NOTE

No. 1498

EFFECT OF LOCAL BOILING AND AIR ENTRAINMENT

ON TEMPERATURES OF LIQUID-COOLED CYLINDERS

By A. P. Colburn, Carl Gazley, Jr.,
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SUMMARY

The design and the optimum operation of cooling jackets for liquid-
cooled engines require an understanding of the heat-transfer character-
istics of the coolants under the special conditions encountered of high heat
fluxes, relatively high metal temperatures, and appreciable amounts of
entrained air in the coolant flow. Owing to the difficulties of evaluating
these conditions on operating engines, a bench-rig apparatus was designed
which would approximate engine-jacket conditions, except that the liquid
flow was maintained uniform around the cylinder in order that the results
could be related to the literature of forced-convection heat transfer.
This report gives a description of the apparatus and data on water and
methanol.

Results are shown as coolant-film coefficients of heat transfer;
these are correlated as dimensionless parameters (j-factors) as a function
of Reynolds number. At low metal-wall temperatures, that is, when the
wall-coolant interface temperature is below the boiling point of the
coolant under existing pressures, data are in close agreement with the
well-known equations for heat transfer in round pipes and in annular
spaces. At high metal-wall temperatures, that is, when the interface
temperature is above the coolant boiling point, local-boiling effects can
be observed. Heat-transfer rates under the latter conditions are found
to depend primarily upon the temperature excess of the wall over the liquid
boiling point and upon the velocity of the coolant past the heating
surface. It is shown that, particularly at low liquid velocities, the
heat-transfer coefficient increases with increasing values of this
temperature difference, with a maximum increase found of 300 percent.
The effect of entrained air is also shown to increase heat-transfer
coefficients, especially at low liquid velocities, with a maximum increase
found of 100 percent. The effect of coolant pressure is merely to increase
the boiling point and so decrease the temperature excess.

The results of this study have been extended to show the typical
effect of the local-boiling phenomenon on metal-wall temperatures. At
low coolant velocities excessive metal temperatures would normally prevail,

but with low-boiling coolants these temperatures are drastically reduced.
The effect is even more spectacular for methanol than for water, owing
to the poorer heat-transfer qualities when nonboiling. For the conditions
chosen, with a methanol coolant velocity of 1 foot per second, the metal-
wall temperature would run 400° F. if the coolant boiling point was higher
than the surface temperature; if the coolant boiling point was, say, 40° F
below the surface temperature, the metal temperature would be only 220° F.

INTRODUCTION

Evaluation of the fundamental relations existing between the rates
of heat transfer and the controlling liquid properties for liquid coolants
in the jackets of liquid-cooled aircraft engines is complicated by a lack
of knowledge of the temperature and velocity distributions within the
jacket, of the phenomena occurring at the metal-liquid interface, of the
effects of coolant pressure and of entrained gases, and of numerous
other variables which are difficult to control and measure. The present
inability to determine with precision these variables in a full-scale
engine assembly or single-cylinder rig indicates a need for a suitable
bench-rig apparatus for this purpose. Although the geometrical patterns
of such an apparatus might not necessarily follow those in an actual engine
jacket, nevertheless much valuable information can be obtained by a funda-
mental approach to the problem with a simple construction permitting
carefully controlled conditions.

A bench-rig apparatus for this purpose should permit an accurate
determination of such factors as coolant velocities, coolant and metal-
wall temperatures, and coolant pressures and be so arranged that various
types of liquid coolants can be studied under similar operating conditions.
It is desirable that the metal-coolant interface be open to visual
observation so that effects such as local boiling can be studied. (Local
boiling is defined as that boiling which occurs in the liquid layer
adjacent to a surface, the temperature of which being above the boiling
point of the liquid and the main body of the liquid being considerably
below the boiling point.) Means of providing for relatively high heat
fluxes are of prime consideration, and a choice between electric, steam,
or gas-combustion heating must be considered. Such a choice would be
influenced by the degree to which individual resistances to heat transfer
between the heating source and the coolant can be evaluated with certainty.

The present study is concerned with the effects of local boiling and
entrained gases on the rates of heat transfer at the solid-liquid interface.
Local boiling undoubtedly occurs in the jackets of liquid-cooled air-
craft engines since portions of the cylinder-wall and head temperatures
are often above the boiling point of the coolant used. Entrainment of air
or other gases is also likely in coolant systems. It is expected that
both local boiling and entrainment of gases would increase the heat-
transfer rate due to increased turbulence.

The only mention of local boiling found in the literature is that given in references 1 and 2 in connection with data in the preheating section of a boiler. In these investigations heat-transfer rates were obtained two to four times those predicted by empirical equations for the warming of liquids. This increased heat transfer was attributed to "(a) increased turbulence resulting from temporary vaporization in the superheated film adjacent to the hot wall, followed by condensation in the bulk of the liquid stream, and (b) turbulence resulting from the surging flow inside the tubes." However, in these investigations the primary interest was the boiling rather than the preheating section, and no correlation of the preheating data was offered except to show that, in the case of benzene-oil mixtures, the preheating rate was approximately twice the predicted values over a large range.

The present report describes a steam-heated apparatus designed for the purpose of studying high heat-transfer rates between hot metal surfaces and coolants in jackets to fulfill the following purposes: (1) To permit a check against literature data for normal conditions, (2) to permit evaluation of the effect of metal temperatures existing above the boiling point of the coolant under varying conditions of flow rate, and (3) to permit determination of the effect of entrained gases. Data are given and discussed for two coolants, water and methanol. Entrainment of air was studied in the methanol only. The authors gratefully acknowledge the assistance of A. Wurster, Andale Company, Philadelphia, in designing the heat-exchange unit.

SYMBOLS

A_o outside area of copper tube including effective heat-transfer area of flange, square feet

C specific heat of coolant, $Btu/(lb)(^{\circ}F)$

D_1 outside diameter of copper tube, feet

D_2 inside diameter of glass tube, feet

D_e equivalent diameter of annulus, feet $\left(D_2 - D_1\right)$

G mass velocity of coolant, pounds/(hr)(sq ft)

H enthalpy of saturated liquid coolant above 32° F, Btu/pound

h_c heat-transfer coefficient of coolant film based on A_o, Btu/(hr)(sq ft)(^{o}F)

h_d heat-transfer coefficient of dirt film based on A_o, Btu/(hr)(sq ft)(^{o}F)

h_{fg} heat of vaporization of steam, Btu/pound

J j-factor, dimensionless $\left((h_c/CG)(C\mu_a/k)^{2/3}(\mu_w/\mu_a)^{0.14} \right)$

k thermal conductivity of coolant, Btu/(hr)(ft)(^{o}F)

N_{Pr} Prandtl number, dimensionless $(C\mu_a/k)$

P steam pressure, pounds per square inch absolute

P_1 pressure on coolant entering exchanger, pounds per square inch absolute

p vapor pressure of coolant, pounds per square inch absolute

Q_a volume flow rate of saturated air through annulus, cubic feet per hour

q_c heat gained by coolant, Btu/hour

q_L heat loss to surroundings, Btu/hour

q_{sc} heat from steam, corrected, Btu/hour

N_{Re} Reynolds number, dimensionless $(D_e G/\mu_a)$

S cross-sectional area of annulus, square feet

t_{bp} boiling temperature of coolant in exchanger, ^{o}F

t_{ca} average temperature of coolant in exchanger, ^{o}F

t_{ci} temperature of coolant entering exchanger, ^{o}F

t_{co} temperature of coolant leaving exchanger, ^{o}F

t_{li} average temperature of wall-liquid interface, ^{o}F

t_s steam temperature corresponding to P, ^{o}F

t_w average temperature of metal wall at thermocouple circle, ^{o}F

Δt_d temperature drop across dirt film, ^{o}F

Δt_w temperature drop from thermocouples to copper-dirt interface, $^{\circ}F$

V linear velocity of coolant in annulus, feet per second

W_a mass flow rate of air, pounds per hour

W_c mass flow rate of coolant, pounds per hour

W_s flow rate of steam condensate, pounds per hour

μ viscosity of coolant, pounds/(hr)(ft)

μ_a viscosity of coolant at t_{ca}, pounds/(hr)(ft)

μ_w viscosity of coolant at t_{li}, pounds/(hr)(ft)

ρ density of coolant, pounds per cubic foot

ρ_a density of coolant at t_{ca}, pounds per cubic foot

DESCRIPTION OF APPARATUS

The test apparatus, although bearing little resemblance to the geometrical configuration of the cooling system of a liquid-cooled internal-combustion engine, was specifically designed to supply fundamental data on heat-transfer rates at a metal-coolant interface which could eventually be related to engine cooling performance. For this reason the experimental exchanger consisted essentially of a thick-walled copper tube surrounded by a glass jacket. The coolant, flowing uniformly upward in the annular space, was the heat-transfer medium under consideration, while steam condensing inside the copper tube served as the source of heat.

Heat Exchanger

Details of the heat exchanger proper are shown by the photographs (figs. 1 and 2). The copper tube, having an outside diameter of 1.660 inches, a length of $14\frac{1}{4}$ inches, and threaded at each end, was equipped with steel heads which served to support the copper tube and glass jacket and to provide for inlet and outlet ports for the liquid coolant.

Steam condensing inside the copper tube served as the heating medium; this particular means was selected after careful consideration indicated that neither electric heat nor gas firing would prove as desirable or convenient for the early experiments. The use of steam

appears to combine the more desirable elements of each of the other
types, since it is easily controlled and permits an independent means
for determining heat-transfer rates. Although the extent to which high
metal-wall temperatures can be obtained is limited by the steam pressure
available, the effect of high temperature differences between metal
wall and coolant can, in effect, be secured through the use of low-
boiling liquids as cooling mediums.

In order to permit visual observation of the metal-liquid interface
so that effects such as local boiling might be studied, the copper
tube was jacketed with a heat-resisting glass tube of 2-inch inside
diameter (nominal size). The latter was held in place with brass glands
bolted to the heads. Synthetic rubber ring gaskets were used to center
the tube and provide a tight seal up to working pressures of somewhat
over 50 pounds per square inch. The ends of the glass tube extended
to within 5/16 inch of the inner wall of each head to aid in obtaining
uniform flow of the coolant entering the annulus; uniform flow was
important so that the data could be compared with literature data on
long annular spaces. An enlargement area in the heads served further
to smooth out the flow and afford a more uniform velocity distribution
around the periphery of the glass tube. For similar reasons, two
$\frac{3}{4}$-inch liquid connections on opposite sides of each header were provided.
The annular space was purposely made small (0.34-in. total clearance)
so that relatively high linear velocities past the heating surface could
be maintained at low quantity throughput of the coolant. In this way a
reasonable temperature rise of the liquid could be obtained to provide
greater precision in evaluation of heat loads.

In order to provide a means for determining individual liquid-film,
heat-transfer coefficients directly, these values being of major importance,
metal temperatures were measured. A number of thermocouples strategically
situated within the metal itself, together with a knowledge of metal
thermal conductivity and heat flux, enabled metal surface temperatures
to be computed readily. This, however, required that the tube be both
relatively short and thick-walled to accommodate the thermocouples.
The use of copper, with its attendant relatively high thermal conductivity,
compensated in part for this added thickness.

Four holes 1/8 inch in diameter were drilled, at 90° intervals,
into each end of the tube to a depth of $4\frac{7}{8}$ inches. In each of these
wells, two copper-constantan thermocouples were inserted, one $4\frac{7}{8}$ inches
deep, the other $1\frac{1}{2}$ inches deep. In order to keep the junctions properly
centered in the wells and to reduce the insulating effect of the holes,
the longer thermocouple wires were inserted in short lengths of
$\frac{1}{8}$-inch by $\frac{1}{16}$-inch copper tubing carefully fitted into the holes so that
there was no side play. Space was provided for the shorter wires by

sawing off one side of the small copper tube down to the $1\frac{1}{2}$-inch depth. The holes were not centered in the copper tube (because of the threading of the ends) but the center lines are 0.205 and 0.135 inch from the outside and inside surfaces, respectively. Thus it was possible to know with certainty the exact location of the 16 junctions with respect to the coolant side of the metal wall and therefore the temperature distribution around the periphery of the tube as well as along its length.

Average inlet and outlet coolant temperatures were measured by thermocouples inserted in tees about 12 inches before and after the headers in the pipe lines entering and leaving the unit. It is believed that sufficient mixing occurred in the fluid streams at these points to insure a proper bulk temperature reading. Ordinary mercury-in-glass thermometers were used for control purposes. An automatic potentiometer was used to measure the temperatures to a precision of about 0.2° F.

The entire heat-exchange unit was so made that it could be dismantled easily and quickly for cleaning the copper and the glass surfaces or for replacing the gaskets and the glass tube in case of failure. During operation the unit was enclosed by a metal screen to provide protection for the glass tube. Essential dimensions of the apparatus and some convenient calculation constants are given as follows.

Inside diameter of copper tube, in. 0.98
Outside diameter of copper tube, D_1, in. 1.66
Inside diameter of glass tube, D_2, in. 2.0
Equivalent diameter of annulus, D_e, ft 0.0294
Cross-sectional area of annulus, S, sq ft 0.00677
Length of glass tube, in. 12
Over-all length of copper tube, in. 14.25
Length of copper tube between flanges, in. 12.625
Outside surface of copper tube between flanges, sq ft 0.457

Auxiliary Apparatus

The general arrangement of the apparatus and interconnecting piping is shown in figures 3 and 4. Liquid coolant was pumped from the large storage tank through a $1\frac{1}{2}$-inch rotameter into the heat-transfer unit. A centrifugal pump having a capacity of 20 gallons per minute at a pressure of 60 pounds per square inch and powered by a 3-horsepower motor was employed. Flow control was maintained by a bypass on the pump, a throttle valve, and a back-pressure valve. Rates of liquid flow were determined by intermittent weighing of the coolant, the rotameter being used solely for control purposes to insure that a constant flow rate was maintained during a run. The hot liquid leaving the heat exchanger was cooled before weighing or returning to storage in a heat exchanger by using water from the laboratory supply as coolant. The degree of cooling was

adjusted by means of a bypass around the cooler. A small vent condenser was provided to reduce vapor loss at the storage and weigh tanks and to permit the escape of air from the system.

Steam at a gage pressure of 125 pounds was available so that metal-wall temperatures up to 325° F could be obtained. A steam-condensate reservoir and subcooler were provided as shown in figure 4. The reservoir was provided with a gage-glass so that the location of the steam-condensate interface could be observed at all times. A small amount of steam was allowed to escape at the vent valve so that any noncondensable gases were removed from the apparatus. Steam-condensate rates were determined by collecting a portion for weighing during a measured period of time, care being taken to adjust the interface exactly to the same level at the end of the period as at the beginning. The subcooler insured that none of the condensate flashed on being let down to atmospheric pressure.

An enlargement of the steam pipe line immediately ahead of the heat exchanger served as an entrainment separator. Any condensate in this main was trapped out through a bleed line and removed. It is believed that this arrangement provided saturated steam at all times for the unit, thus eliminating the need for determination of steam quality during a run. As a large amount of trouble was caused by dirt in the steam line that promoted dropwise condensation, a strainer was installed ahead of the reducing valve, and the entrainment separator ahead of the heat exchanger was replaced by a cyclone separator. Even so, it was necessary to flush out the steam side of the heat exchanger with acetone or methanol to remove oily dirt. The entire apparatus and all piping were thoroughly lagged to reduce heat losses to a minimum and such slight heat loss as did exist was determined.

For studying the effect of entrained air in the methanol, air was supplied by a compressor pump at a pressure which could be held approximately constant at any desired value less than 40 pounds per square inch. The air was metered by passing it through a $\frac{1}{4}$-inch rotameter which had been previously calibrated. From the rotameter, the air passed through a $\frac{1}{8}$-inch pipe and entered the coolant stream through a tee located about 2 feet ahead of the heat-exchanger unit. The temperature of the air in the rotameter was read by a thermocouple inserted in a tee immediately preceding the rotameter, while the pressure was read from a pressure gage inserted in the airline immediately following the rotameter. A needle valve placed in the airline just before the point of entry into the coolant stream permitted the flow of air to be closely regulated.

While runs without air were being made, the coolant circulating system was airtight, except for the brief interval of time required for determination of the mass flow rate. The inlet and outlet of the

weighing tank were surrounded by cloth rings which served to minimize
the escape of coolant vapor into the air of the laboratory and also to
prevent absorption of atmospheric moisture by the methanol.

TEST PROCEDURE

Water Runs

In the runs in which water was used as the coolant, the operation
of the apparatus was relatively simple and straightforward. The pump
was started and the water flow rate and back pressure on the heat-
exchanger unit regulated to the desired value by means of the throttle
valve, pump bypass valve, and back-pressure valve. Heating steam was
turned on, the condensate reservoir vented to remove noncondensable
gases, and a steady flow of cooling water put through the condensate
cooler. The circulating coolant slowly rose in temperature to the desired
inlet value, at which time cooling water to the auxiliary cooler was
turned on and the flow rate adjusted.

Readings were then taken and recorded at 5-minute intervals of the
temperatures of the coolant entering and leaving the heat-transfer
unit, the coolant leaving the cooler, the coolant entering the storage
and weighing system, and of the rotameter float position and the steam
pressure. When all readings became constant and thermal equilibrium
appeared to have been attained, the condensate rate was measured. The
temperatures of the coolant entering and leaving the heat-transfer unit,
of the steam, and of the copper tube (at the 16 points described in
the section entitled "Heat Exchanger") were then taken and recorded. The
condensate rate was again measured. If steady flow rates and thermal
equilibrium had not prevailed during the course of the foregoing
measurements, slight adjustments were made where necessary until a new
equilibrium condition was obtained, at which time all measurements were
repeated.

On completion of the foregoing operations, the coolant flow rate
as indicated by the rotameter was checked by direct weighing. Steam
flow and cooling water to the auxiliary cooler were turned off and the
coolant stream diverted to the weigh tank where a given quantity
(about 100 lb, the amount depending on the rate of flow) was accurately
weighed and the time of efflux carefully determined with a stop watch.
During this period the temperature of the coolant at the rotameter was
found to remain essentially constant and equal to its temperature during
the course of the actual run. The rotameter float position was also
carefully observed and any minor deviations from previous settings corrected.
Barometric pressure and room temperature were also noted and recorded.

After an early series of runs had shown that water acted to cause
an oxide and dirt film on the copper surface, a series of tests was
made to determine the effect of the addition of small amounts of some
inhibitor to the water. Experiment showed that the addition of about
0.1 percent by weight of disodium acid phosphate retarded the formation
of rust in the piping system and reduced the rate of deposition of
dirt on the copper tube. Experiment also showed that distilled water
was superior in this respect to the water from the laboratory supply.
As a result of these tests, distilled water with the addition of
0.1 percent of disodium acid phosphate was employed.

In order to evaluate the effect of the dirt film, a series of runs
was made periodically under as nearly exact conditions of operation as
possible. By assuming a "fouling factor" of zero for any run made with
the copper tube newly cleaned, fouling factors could be calculated
by subtracting from the liquid-film resistance for each of these runs
that for the newly cleaned tube. All the "standard" runs were made at
inlet coolant temperatures around 117° F, heat loads of about
60,000 Btu per hour, and coolant rates of about 16 gallons per minute.

Methanol Runs

The test procedure for runs without entrained air and employing
methanol as coolant was identical with the test procedure used for runs
with water as coolant. It was found that, in general, equilibrium conditions
were attained more rapidly with methanol as coolant than they had been
attained when water was used as the cooling medium. This is a natural
result in view of the lower heat capacity of methanol.

In order to check on the possible formation of a dirt film on
the coolant side of the copper tube, a standard run was repeated at
regular intervals. In contrast with the effects observed with water,
it was found that the heat-transfer coefficient remained essentially
constant, this fact indicating a negligible formation of dirt film.

As has already been mentioned, the deposition of oily dirt on the
steam side of the heat exchanger sometimes caused dropwise condensation
of the steam in the form of drops. This condition was easily detected
by means of the resulting high tube-wall temperatures and nonuniform
temperature distributions. Consequently, at the start of each day's
series of runs, conditions for a standard run were duplicated. Equilibrium
was attained in about $\frac{1}{2}$ hour, and the tube-wall temperatures were then
quickly read and compared with the known values for a clean tube. If
they checked, work on the other runs could proceed with confidence; if
they did not check, the rig was shut down and remedial measures taken.
Usually a simple flushing with an organic solvent was sufficient, but it
was occasionally necessary to dismantle the heat exchanger and give the
copper tube a thorough cleaning with scouring powder.

Methanol Runs with Entrained Air

The effect of entrained air on the heat-transfer properties of the coolant was studied in the following manner. A run was first made without air, equilibrium being reached and a complete set of readings taken. On keeping all other valve settings fixed, the air valve was then opened and a small amount of air allowed to enter the coolant stream. When a new equilibrium had been reached, a second complete set of readings was taken, including determination of the coolant mass flow rate. This was then repeated once or twice more for higher air-flow rates. In this way, a set of three or four runs was made in which coolant flow conditions remained essentially constant except for varying amounts of entrained air. A total of 6 such sets of runs (including 22 separate runs) was made, 3 boiling and 3 nonboiling, at high, intermediate, and low coolant flow rates. The runs of each set were assigned the same serial number, with letters following to indicate the amount of air.

Determination of Heat Loss to Surroundings

Despite the thorough lagging of all steam and condensate lines, small heat losses to the room undoubtedly occurred. A series of blank runs was therefore made with no flow of coolant through the unit at a number of steam pressures from 28 to 110 pounds per square inch. The rate of flow of condensate was carefully measured over periods of about 30 minutes and heat losses calculated. These results were plotted as heat loss in Btu per hour against the difference between steam and room temperatures.

METHOD OF CALCULATION

The method of calculation employed can best be followed by reference to tables I, II, and III, wherein observed and calculated data are given in detail. If a series of readings was taken over a period of time, as when temperatures were read at 5-minute intervals during steady-state conditions, average values are given.

Heat-Transfer Calculations

Heat-transfer rates and heat balances were computed in a normal manner. All data for steam were taken from the tables of Keenan and Keyes (reference 3). In the runs with water, the heat gained by the coolant was simply calculated from the flow rate and temperature rise as follows:

$$q_c = W_c c \left(t_{co} - t_{ci} \right) \tag{1}$$

The use of methanol as a coolant necessitated a change in the calculation procedure since the specific heat of methanol varies considerably with temperature (in contrast with the specific heat of water, which differs from unity by less than 0.7 percent over the entire temperature range from 40° F to 212° F). The heat gained by the methanol was accordingly calculated from the difference in heat content of the coolant at the inlet and outlet temperatures as follows:

$$q_c = W_c \left(H_{co} - H_{ci} \right) \tag{2}$$

The heat from the steam q_{sc} is taken as the product of the condensate rate and latent heat of vaporization less heat loss to the surroundings as follows:

$$q_{sc} = W_s h_{fg} - q_L \tag{3}$$

Because steam was in contact with condensate below the unit, the condensate could be expected to leave the reservoir at the boiling point. Since the steam entering the unit was generally dry and saturated, only latent heat need be considered. The small heat loss q_L was obtained from data obtained on the blank runs.

The boiling point of the coolant in the annulus of the exchanger is based on readings of the pressure gage located just upstream of the unit. The pressure drop across the annulus was generally measured with a water manometer; this drop was usually small compared with the actual static pressure on the coolant, and no refinement of the boiling temperature because of pressure drop was made.

In order to calculate the heat-transfer coefficient from metal surface to coolant, it is necessary to know the average coolant and the average surface temperatures. Because of the small temperature difference, the arithmetic average of inlet and outlet coolant temperatures is satisfactory for the former. The average of the 16 temperatures at the 4 elevations and the 4 angular positions of the metal wall was found to give an excellent approximation of the average temperatures of the metal at a depth of 0.205 inch from the coolant surface, as can be seen by the examples shown by figures 5 and 6. The average temperature difference across this thickness of metal was calculated from the value of heat flux and the conductance of the metal, which latter value is around 11,000 Btu/(hr)(sq ft)(°F).

In order to take care of end effects, values of the liquid-film coefficient h_c are based on a corrected outside surface area of the copper tube. The metal heads conducted a small portion of heat to the

coolant, and it was convenient to correct for this effect by increasing the value of the heat-transfer surface on which the coefficients are based. The calculation of the effective increase in area is shown in appendix A by considering the two heads as fins; this increase amounts to 4.6 percent in the case of water and 9.6 percent in the case of methanol.

When a dirt film was known to have built up on the tube surface over a period of time, the resistance of and the temperature drop across this film were evaluated and a suitable correction applied. The method of determining this resistance by repeating periodically a so-called standard run was previously described. A plot of dirt-film resistance against run number gave curves from which this value could be obtained. Furthermore, coefficients computed for runs subsequently made from time to time on the newly cleaned tube agreed very well, thus indicating the validity of this method of approach. Values of the dirt-film resistance $1/h_d$ used in the calculations are given as item 16 in tables I, II, and III. Sources of data used for the physical properties of methanol are given in appendix B; a brief summary of the data is given in table IV.

Air-Flow Calculations

The rotameter used for the metering of air was first calibrated in the following manner. Known quantities of air from a calibrated gas-holder were allowed to pass through the rotameter for several different readings of the rotameter, and the times of efflux were recorded. Atmospheric pressure, air temperature, and pressure drop across the rotameter were also recorded. From these data, air densities and volumetric flow rates corresponding to the various readings of the rotameter were computed. The calibration curve was drawn by plotting as abscissa the rotameter readings and as ordinate the product of the actual flow rate in cubic feet per hour and the dimensionless ratio $\left(\rho/\rho_o\right)^{1/2}$, where ρ represents actual air density and ρ_o represents air density at some fixed conditions of temperature and pressure. This method of plotting gives a single curve which is valid over a large range of air density. The actual value of ρ_o used is clearly immaterial, and for convenience the value 0.075 pound per cubic foot, corresponding to air at 20° C and 1 atmosphere pressure, was used.

In the calculations involving air data, the density of air passing through the rotameter was calculated from its observed temperature and pressure, and its volumetric flow rate was then computed from the rotameter calibration curve. Values of $\left(\rho/\rho_o\right)^{1/2}$ varied from 1.40 to 1.74 during actual runs, whereas the value of this ratio during calibration was 0.985. From the knowledge of the density and volumetric flow rate of the air through the rotameter, its mass flow rate was calculated.

The volume of air passing through the heat exchanger was computed from knowledge of the pressure and average temperature of the coolant. Since the bubbles of entrained air were presumably saturated with methanol vapor by the time they reached the heat exchanger, the volume of air was corrected for the effect of the vapor pressure of methanol.

Method of Correlation

In order that the heat-transfer coefficient h_c can be correlated with fluid properties and flow conditions and also be compared with data of other investigations, the results were computed as j-factors according to the equation

$$ \mathbf{j} = \left(\frac{h_c}{CG}\right)\left(\frac{C\mu_a}{k}\right)^{2/3}\left(\frac{\mu_w}{\mu_a}\right)^{0.14} \tag{4} $$

and the Reynolds number

$$ N_{Re} = \frac{D_e G}{\mu_a} \tag{5} $$

Equation (4) is essentially that used by Colburn (reference 4) for correlating heat-transfer data for fluids in round pipes but includes the power function of the viscosity ratio recommended by Sieder and Tate (reference 5) to correct for the fluid-film viscosity. The Reynolds number is based on the equivalent diameter of the annulus $\left(D_2 - D_1\right)$ and in this form possesses the advantage of permitting a more direct comparison of the data obtained for an annulus with the recommended heat-transfer relations for fluids in round pipes. Furthermore, Carpenter, Colburn, Schoenborn, and Wurster (reference 6) have shown that this is the proper Reynolds number to use in the case of flow through annular spaces. This method of treatment is convenient also in utilizing fluid properties evaluated at the average coolant temperature t_{ca}.

For purposes of further treatment of the data and in particular to establish the effect of vaporization of the coolant at the tube surface, it was necessary to know the boiling point of the coolant under existing conditions of operation and the average as well as the maximum temperature at the coolant-metal interface. The latter values were computed by subtracting the sum of the temperature drops across

the tube wall and dirt film from the average tube-wall temperature t_w
and are given in tables I, II, and III as items 21, 18, and 19,
respectively.

DISCUSSION

Heat Balance

Values of the heat load based on the coolant stream and on the
steam condensate rate generally agreed very well. Deviations in the
heat balances are shown in tables I, II, and III (item 11) for each
run. As can be seen, deviations are within 3 percent for about 60 percent
of all runs and within 5 percent for 85 percent of all runs. Despite
the occasional larger deviations, which doubtless result from the small
coolant temperature rise encountered at high coolant rates, the good
agreement normally obtained serves to emphasize the reliability of the
data secured on this type of rig.

Tube-Wall Temperature Distribution

The type of temperature distribution obtained from the 16 tube-wall
thermocouples is represented by using polar coordinates in figures 5
and 6. The data shown are for run 59 (water) and run 93 (methanol) and
demonstrate the remarkable symmetry that can be obtained. Similar data
for all runs are given in tables I, II, and III, wherein the letters A
to D refer to locations vertically from bottom to top and the numbers 1
to 4 to the angular position around the tube.

The temperature distributions for some of the early runs did not
show as excellent symmetry as the ones illustrated. This was found,
after extensive tests had been made, to be due to dropwise condensa-
tion of the steam in the form of drops at certain points on the inner
tube wall. Initially, a large number of runs was made with lauryl
thiocyanate used as a promoter of dropwise condensation so as to
obtain high coefficients on the steam side, but nonuniform condensa-
tion resulted in such erratic patterns that its use was discontinued.
By keeping the inner tube surface and interconnecting piping scrupulously
clean and free from oil films, uniform film-type condensation was
secured with resulting uniform and reproducible tube-wall temperature
distributions. It is believed that film-wise condensation of steam
existed during all runs reported herein.

In figure 7 average temperatures at a given cross section of the tube
are plotted as functions of tube length. Terminal temperatures are shown
also for both the coolant (water) and steam, the dashed lines indicating
the trend between end points. The small temperature rise of the coolant
compared with the temperature difference between wall and coolant justifies

the procedure of determining the mean temperature difference by subtracting
the average (of inlet and outlet) coolant temperature from the average
wall temperature (based on the 16 thermocouple readings and the temper-
ature drop through the metal).

It should be noted that the decreasing wall temperature from top
to bottom is a result of both the increasing thickness of the steam-
condensate film and the increase in the coolant-film coefficient. Since
the coolant flowed upward in the tube, the coefficient at the bottom
would be greater than the average value because of turbulence and the
fact that the velocity distribution had not been established. However
the latter effect is relatively small compared with the change in the
steam-film resistance. Thus the variable temperature drop from metal to
coolant is a measure of the variable heat flux, which, as in an engine,
is greatest at the top and progressively decreases down the cylinder.
For example, in run 59 for which the temperatures are given in figure 7,
with an average heat flux of 60,900 Btu/(hr)(sq ft), the heat flux at
the upper end of the tube is estimated as 98,000 Btu/(hr)(sq ft) and at
the lower end, 33,000 Btu/(hr)(sq ft). These values are quite representative
of full power conditions of some reciprocating engines.

In figure 8 the distribution of temperature with tube length is
shown for low and high coolant (methanol) flow rates, both with and
without local boiling and/or air entrainment. It is seen that the
temperature distributions are roughly linear for high coolant velocities
but deviate quite considerably from linearity for low coolant velocities.
This is probably due to the effect of free convection. At low flow
rates, the increased mixing of coolant due to convection near the top
(outlet) of the tube causes a more .complete equalization of coolant
temperatures with the result that the top of the tube may be cooler than
the part immediately below.

Nonboiling Data

Inasmuch as the apparatus was designed to give uniform flow of
coolant so as to permit exact comparison of the results with extensive
heat-transfer data from the literature for flow in pipes and in annular
spaces, the data have been correlated by a method permitting such a
comparison. It was expected that, if the data were reliable, the runs
in which no local boiling occurred would show good agreement with the
literature. In figure 9 the nonboiling data, for both water and methanol,
are shown. In case of laminar flow through annuli, the use of the
following equation is recommended in reference 6:

$$\left(\frac{h_c}{CG}\right)\left(\frac{C\mu_a}{k}\right)^{2/3}\left(\frac{\mu_w}{\mu_a}\right)^{0.14} = 1.86\left(\frac{D_eG}{\mu_a}\right)^{-2/3}\left(\frac{L}{D_1 + D_2}\right)^{-1/3} \qquad (6)$$

It is seen that the data are somewhat low compared with equation (6) but this may possibly be due to the effects of free convection. The data of Jurgenson and Montillon (reference 7) indicate that free convection forces decrease the heat-transfer coefficient for upward flow.

For turbulent flow in pipes the Seider and Tate equation (reference 5) is (as given by McAdams (reference 8)):

$$\left(\frac{h_c}{C G}\right)\left(\frac{C\mu_a}{k}\right)^{2/3}\left(\frac{\mu_w}{\mu_a}\right)^{0.14} = 0.027\left(\frac{D_e G}{\mu_a}\right)^{-0.2} \tag{7}$$

while for turbulent flow in annuli Davis (reference 9) recommends

$$\left(\frac{h_c D_1}{k}\right) = 0.031\left(\frac{D_1 G}{\mu_a}\right)^{0.8}\left(\frac{C\mu_a}{k}\right)^{1/3}\left(\frac{\mu_a}{\mu_w}\right)^{0.14}\left(\frac{D_2}{D_1}\right)^{0.15} \tag{8}$$

It is an interesting coincidence that for the geometry involved in the present apparatus, the Davis equation reduces to

$$\left(\frac{h_c}{C G}\right)\left(\frac{C\mu_a}{k}\right)^{2/3}\left(\frac{\mu_w}{\mu_a}\right)^{0.14} = 0.023\left(\frac{D_e G}{\mu_a}\right)^{-0.2} \tag{9}$$

which is equivalent to the Colburn equation (reference 4) with the Seider and Tate viscosity ratio modification (reference 5). Figure 9 shows that the data fall between equations (7) and (9). It may be noted that figure 9 is analogous to figure 13 given by Bernardo and Eian (reference 10) which provides heat-transfer data for various nonboiling coolants inside a heated tube; actually the data from the two studies would practically coincide, thus lending support to the general relation for nonboiling coolants.

It may be noted that the methanol data of the present investigation in the turbulent region fall somewhat higher than the water data. The fact that this discrepancy occurs in the turbulent and not in the laminar region is difficult to understand.

The discrepancy between the correlations of water and methanol data at high coolant velocities is a matter of relatively minor importance and in no way affects the validity of the main results of this investigation,

namely, the effects of local boiling and entrained air on heat-transfer properties of liquid coolants in annular spaces. It would be expected that both local boiling and the presence of entrained air would increase the rate of heat transfer because of the slightly increased volocity (for a given coolant flow rate) and increased turbulence. The separate effects of local boiling and entrained air are discussed in the following paragraphs.

Local Boiling without Air

When the metal surface exceeded the boiling point of the coolant at the existing pressure, even though the bulk temperature of the coolant was considerably below the boiling point, formation of vapor bubbles at the metal surface could be observed. The boiling phenomena were clearly evident, particularly after the tube had been freshly cleaned, and a brief description is of general interest. Small bubbles of vapor were seen to form and cling to the tube wall - then gradually to be torn away to become dissipated in the bulk of the flowing coolant stream (where the temperature was still below the boiling point). On increasing the pressure on the coolant, bubble formation stopped and the bubbles remaining were torn away.

When a dirt film had formed on the tube wall and as fouling conditions increased, it was not possible to observe the metal-liquid interface clearly. Vapor bubbles did not appear to form on the metal surface, however, nor to cling to the wall but were quite visible in the liquid stream. As coolant pressure was increased, rate of bubble formation decreased and finally ceased altogether.

In some runs active boiling was evident only at the upper portion of the tube, so for this reason maximum values of t_{li} were computed for the top portion of the tube and are given in tables I, II, and III. By adjustment of the pressure on the coolant, a rather sharp line of demarcation between boiling and nonboiling areas could be made to move up or down the tube at will. Some nonuniform temperature patterns obtained are doubtless due to such phenomena. If the temperature excess of the metal wall over the boiling point of the liquid was small (less than 10° F), only a few bubbles of vapor were formed, and these disappeared almost the instant they were torn loose from the wall. As the temperature excess was increased, the rate of bubble formation increased and the bubbles showed less tendency to disappear. The general appearance of the tube while local boiling was taking place was the same for both water and methanol. In this connection the problem arises as to the parameter that is best to use to denote the degree of local boiling. As previously noted (see fig. 8) the wall-surface temperature increases from bottom to top of the tube so that local boiling may occur at the top of the tube even though the average wall temperature is below the boiling temperature of the coolant. Thus the use of the parameter $\left(t_{li} - t_{bp}\right)$ might involve

the use of negative values, cognizance being taken of the fact that local boiling could occur at negative values. On the other hand, the use of $\left(t_{li_{max}} - t_{bp} \right)$ would not be a proper measure of average conditions. The most exact method would involve plotting the temperature distribution along the length of the tube and graphically determining the mean excess above the boiling point of the coolant. For the purposes of this report the quantity $\left(t_{li} - t_{bp} \right)$ will be used as an approximation since it allows much simpler and more direct calculation. However it should be recognized that negative values do not necessarily mean that boiling is not occurring. The condition for local boiling is that $t_{li_{max}}$ be greater than t_{bp}.

The fact that this local boiling phenomenon increases the heat-transfer rate markedly under certain conditions can be seen from the boiling data in figure 10. It will be seen that these are higher the greater the temperature excess and the lower the Reynolds number. The effect of the excess of surface temperature over the coolant boiling point in increasing heat-transfer rate is approximately the same for both coolants, water and methanol, as can be seen from the values of $\left(t_{li} - t_{bp} \right)$ shown adjoining the experimental points. It would be expected that this effect would be about the same for any pure coolant, although possibly not for mixtures. In case of mixtures the evaporation of a portion of the liquid would increase the boiling point of the remaining liquid; this might therefore reduce the effect.

In figure 11 the heat-transfer coefficient of water is plotted against the linear coolant velocity V. Lines of approximately constant temperature differences $\left(t_{li} - t_{bp} \right)$ of 0, 10, 20, and 30° F are indicated as parameters. An important conclusion is that with low boiling coolants the heat-transfer rate does not fall off with decreasing velocity in the engine jacket to anything like the decrease for high boiling coolants.

Figure 12 shows the variation of heat-transfer coefficient of methanol with linear velocity of flow for various values of the average temperature excess. In both figures 11 and 12, the curve for nonboiling data, to the right of V = 1 foot per second, has been drawn as a straight line of slope 0.8 in accordance with usual heat-transfer data in turbulent flow, and agreement is seen to be excellent. The methanol data are somewhat more complete than the water data and bring out several interesting points not discernible from the latter. As in the case of water, the heat-transfer coefficient is seen to increase as the average temperature excess $\left(t_{li} - t_{bp} \right)$ increases, though the relative increase decreases as the velocity of flow increases. Thus, for example, a temperature excess of 10° F increases the heat-transfer coefficient by 47 percent above the nonboiling value for a flow velocity of 0.5 foot per second, though a temperature excess of over 30° F is required to produce the same increase at the higher flow velocity of 3 feet per second.

The method of plotting used in figures 11 and 12 is useful only in determining the effect of velocity on the rate of heat transfer for one fluid at a given temperature. Different fluids or even the same fluid at different temperatures cannot be compared since the physical properties as well as the velocity influence the rate of heat transfer. Figure 13, in which the j-factor is plotted against the average temperature excess with Reynolds number as parameter, allows comparison of the methanol and the water data. Scattering of some of the data in this and the preceding figures is probably due to nonuniformity in local boiling from top to bottom of the tube. Occasionally, bubbles of vapor were observed at only a portion of the tube surface. It appears that a sufficiently high temperature excess produces some effect even at high flow rates. Higher temperature excesses were obtained in using the lower-boiling methanol as coolant, and it can be seen that the effect of increasing the Reynolds number is simply to increase the threshold value of the temperature excess required to produce a significant increase in the heat-transfer coefficient. It will be noted that the threshold value of the average temperature excess is lower for water than for methanol. The reason for this cannot be stated definitely because of the little that is known of boiling heat transfer. It is known that the properties of the liquid and the type of surface influence the rate of boiling. It may be noted that the critical value of Δt (i.e., the value of Δt at which the maximum heat flux occurs and above which the flux begins to decrease because of formation of a film of vapor over the heating surface) for water boiling at a copper wall is considerably lower (see reference 8) than that of methanol. This indicates the more facile formation of vapor bubbles in the case of water and hence explains the lower threshold values obtained herein.

Figure 13 may be compared with figure 170 given by McAdams (reference 8). In the latter figure, $j(N_{Re})^{0.2}$ is plotted against the temperature excess for heat transfer in the tubes of a forced-circulation evaporator in which both warming and actual vaporization took place. Instead of the rough differentiation of McAdams between Reynolds numbers above and below 65,000, it appears that a separate curve for each Reynolds number is obtained even if the curves are brought together at low values of the temperature excess by multiplying the j-factor by $(N_{Re})^{0.2}$.

Entrained Air without Local Boiling

When air was introduced into the coolant stream, the air was broken up into bubbles and more or less evenly distributed throughout the stream. The size of the bubbles and the evenness of the distribution depended on the velocity of coolant flow. Thus, for a Reynolds number of about 20,000, the bubbles of air were small (about 0.5 mm in diam.) and evenly distributed. A Reynolds number of 10,000 produced bubbles of slightly larger size, though their distribution was still very

uniform. When the Reynolds number was decreased to 4000, however, the flow velocity was insufficient to break up the air stream into small bubbles; the size of the bubbles simply increased as the rate of air flow was increased until they had a volume about one-third the volume of the entire annular space. The distribution of these large bubbles, while irregular at any given instant of time, nevertheless was fairly uniform when averaged over longer intervals of time.

The action of the entrained air in increasing the heat-transfer coefficient appears to be due to a combination of two related factors: (1) increased turbulence, and (2) increased linear velocity of the coolant for a given rate of coolant mass flow. The increased linear velocity is due to the fact that the entrained air decreases the average density of coolant-air mixture, and hence, for a given mass flow rate, the linear flow rate must increase. Since both the increase in turbulence and the increase in linear flow rate are primarily governed by the relative volume rather than the mass of the entrained air, the data have been correlated on the basis of the percentage by volume of air (plus methanol vapor) in the heat exchanger.

As can be seen from figure 14, the effect of entrained air is qualitatively similar to the effect of local boiling. The increase in the heat-transfer coefficient is greater for low coolant velocities and increases with increasing amounts of air. The velocity of flow used in figure 14 is not the actual linear flow rate but rather the flow rate that would exist if there were no air and is obtained by dividing the coolant mass flow rate by the density of the coolant. In this way the graph shows the over-all effect of the entrained air on the heat-transfer coefficient; if the actual velocity of the mixture were plotted, only the effect of increased turbulence would show up on the plot, and the effect of the increased velocity would not be apparent.

Entrained Air with Local Boiling

When local boiling was taking place, the effect of entrained air was to increase the heat-transfer coefficient still further, although the amount of this additional increase was considerably less than that caused by air alone without boiling. This can be seen by a comparison of figures 14 and 15. In a sense, then, the effects of air and boiling are complementary, that is, the effects of boiling become less as the amount of air increases, while the effect of air becomes less as the amount of boiling increases. Both effects become less as the Reynolds number increases.

The effect of air on boiling runs is shown in figure 15, where heat-transfer coefficients and average temperature excesses are plotted as functions of the percentage of air for various values of the Reynolds number. It is seen that increasing the amount of entrained air tends to cool the metal wall and thus lower the average temperature excess, while at the same time the heat-transfer coefficient is increased. Since a decrease in the average temperature excess would, by itself, tend to

lower the heat-transfer coefficient, it follows that the effect of the
air in raising the heat-transfer coefficient is sufficient to outweigh
the effect of lowered temperature excess.

Application to Engine Cooling

Since the important feature in engine work is the wall temperature
rather than heat-transfer rates in themselves, the results of this
investigation have been used to calculate typical values of metal
temperatures with and without local boiling. Figures 16 and 17 have
been prepared for the two values of heat flux of 100,000 and
50,000 Btu/(hr)(sq ft), which are representative of average rates
through the head and the barrel, respectively, of aircraft engines under
full power. The coolant (water) is assumed to be at 190° F and the
curves show the metal temperature as a function of coolant velocity.
If the boiling point of the coolant is above the metal temperature, the
latter becomes excessive at low coolant velocities, but if the boiling
point of the coolant is as much as 30° F below the metal temperature, the
metal temperature stays reasonably low even at low coolant velocities.

Figure 18 has been prepared, analogous to figures 16 and 17, to
show the cooling effect of the local boiling of methanol. By assuming
a heat flux of 50,000 Btu/(hr)(sq ft) and an average coolant temperature
of 110° F, average wall temperatures have been calculated on the basis of
figure 12. The results are comparable with those obtained for water,
when allowance is made for the fact that methanol has a generally lower
heat-transfer coefficient. Because of the generally low heat-transfer
rates to organic liquid in forced convection, it is to be expected that
other organic coolants would also exhibit large local-boiling effects.

A set of curves could likewise be drawn to show the effect of entrained
air on the metal-wall temperature. It can be seen from figure 14, for
instance, that a 15-percent volume of entrained air will have roughly
the same effect on the heat-transfer coefficient as an average temperature
excess of 30° F, and a combination of air and boiling could be expected
to show a somewhat greater effect than the same amount of either air
or boiling separately.

SUMMARY OF RESULTS

An investigation has been made of the effect of local boiling and
air entrainment on temperatures of liquid-cooled cylinders. Results
are shown as coolant-film coefficients of heat transfer; these are
correlated as dimensionless parameters (j-factors) as a function of
Reynolds number. At low metal-wall temperatures, that is, when the wall-

coolant interface temperature is below the boiling point of the coolant under existing pressures, data are in close agreement with the well-known equations for heat transfer in round pipes and in annular spaces. At high metal-wall temperatures, that is, when the interface temperature is above the coolant boiling point, local-boiling effects can be observed. Heat-transfer rates under the latter conditions are found to depend primarily upon the temperature excess of the wall over the liquid boiling point and upon the velocity of the coolant past the heating surface. It is shown that, particularly at low liquid velocities, the heat-transfer coefficient increases with increasing values of this temperature difference, with a maximum increase found of 300 percent. The effect of entrained air is also shown to increase heat-transfer coefficients, especially at low liquid velocities, with a maximum increase found of 100 percent. The effect of coolant pressure is merely to increase the boiling point and so decrease the temperature excess.

The results of this study have been extended to show the typical effect of the local-boiling phenomenon on metal-wall temperatures. At low coolant velocities excessive metal temperatures would normally prevail, but with low-boiling coolants these temperatures are drastically reduced. The effect is even more spectacular for methanol than for water, owing to the poorer heat-transfer qualtities when nonboiling. For the conditions chosen, with a methanol coolant velocity of 1 foot per second, the metal-wall temperature would run 400° F if the coolant boiling point was higher than the surface temperature; if the coolant boiling point was, say, 40° F below the surface temperature, the metal temperature would be only 220° F.

University of Delaware
Newark, Del., August 14, 1947

APPENDIX A

HEAT-TRANSFER CORRECTION FOR STEEL HEADS

Consideration of the heat-exchange unit shows that, although the bulk of the heat transfer to the coolant is effected through the copper tube, a portion of the total heat load is transferred by conduction through the steel heads. This additional transfer of heat is most conveniently accounted for by an estimation of the extra effective surface area contributed by each head. By assuming the heads to behave as parallel-sided circumferential fins, it is possible to calculate a suitable fin efficiency from which the increase in surface area can be evaluated. For this case the following dimensions are employed:

Area of exposed copper tube (outside diam.), sq ft 0.457
Fin root radius, R_b, ft (0.83 in.) 0.0692
Fin width, w, ft (1.045 in.) 0.087
Average fin thickness, t, ft (11/16 in. = 0.687 in.) 0.0572
Total surface area of 2 fins, sq ft $\left(\dfrac{2\left[(1.875)^2 - (0.83)^2\right]}{144}\right)$ . . 0.1232
Effective fin width, w', ft $(w + 1/2t = 1.045 + \dfrac{0.687}{2}$
$= 1.389$ in.) 0.1157

The fin effectiveness for straight fins, as given by Bierman and Pinkel (reference 11), may be written:

$$\eta = \frac{\tanh a\,w'}{a\,w'}$$

where

$a = (h/kt)^{1/2}$ for one side of fin

h   surface film coefficient

k   thermal conductivity

Water.- On assuming a heat-transfer coefficient h = 1500 and a thermal conductivity k = 26 (for steel),

$$a = \left(\frac{1500}{26 \times 0.0572}\right)^{1/2} = 31.75$$

The fin effectiveness then becomes (for straight fins)

$$\eta = \frac{\tanh{(31.75)(0.1157)}}{31.75 \times 0.1157} = 0.272$$

For a circular fin this value is corrected by using figure 12 given by Harper and Brown (reference 12). For a value of $R_b/(R_b + w) = 0.375$, a correction ($f' = -0.1$, approximately) is found. The corrected fin effectiveness thus becomes

$$\eta_{cor} = 0.172$$

The extra effective surface $= 0.172 \times 0.1232 = 0.0212$ square foot, or an increase in surface of $\frac{0.0212}{0.457} \times 100 = 4.6$ percent. The total corrected effective heat-transfer surface is, then, 0.478 square foot, equivalent to an effective tube length of 13.2 inches.

Methanol.- On assuming an average heat-transfer coefficient $h = 500$ and proceeding as before,

$$\eta = 0.458$$

$$\eta_{cor} = 0.358$$

The extra effective surface $= 0.358 \times 0.1232 = 0.0441$ square foot, or an increase in surface of $\frac{0.0441}{0.457} \times 100 = 9.6$ percent. The total corrected effective heat-transfer surface is 0.501 square foot, equivalent to an effective tube length of 13.8 inches.

APPENDIX B

SOURCES OF PHYSICAL PROPERTIES OF METHANOL

Data on the heat content of liquid methanol were obtained from reference 13. The following formula was given:

$$H' = 23.529(\theta/10)^2 + 0.010036(\theta/10)^3 \tag{B1}$$

where H' is the heat content or enthalpy of the saturated liquid above $0°$ C expressed in joules per gram and θ is the temperature in $°C$. Within the temperature range for θ from $40°$ C to $110°$ C, this formula agrees with the observed values to within 0.05 joule per gram. If H is expressed in Btu per pound, the formula becomes

$$H = 10.1175(\theta/10) + 0.11107(\theta/10)^2 + 0.0043155(\theta/10)^2 \tag{B2}$$

If equation (B2) is differentiated and multiplied by 5/9 to convert $Btu/(lb)(°C)$ to $Btu/(lb)(°F)$, the following equation is obtained:

$$C = 0.56208 + 0.01234(\theta/10) + 0.0007192(\theta) \tag{B3}$$

where C is in $Btu/(lb)(°F)$ but θ is still in $°C$.

An extended graph of equation (B2) permits differences in heat content to be read with sufficient accuracy for temperature rises greater than about $3°$ C or $5°$ F. For smaller temperature rises, better accuracy is obtained by using equation (B3) to compute the specific heat at the mean temperature and multiplying this by the temperature rise to obtain the increase in heat content.

Data on thermal conductivity of liquid methanol were obtained from reference 14. Variation of conductivity with temperature was found to be linear over the range $10°$ C to $50°$ C and is given by the equation $k' = 0.00054 - 0.00000150t$, where t is in $°C$ and k' is in $calories/(sec)(cm)(°C)$. If k is expressed in $Btu/(hr)(ft)(°F)$ and t in $°C$, the following equation results:

$$k = 0.1306 - 0.000363t \qquad \text{(B4)}$$

Data on viscosity were obtained chiefly from reference 15. The logarithm of the viscosity was plotted against the reciprocal of the absolute temperature on rectangular paper, and the points were seen to fall along a smooth curve, the greatest variation being less than 2 percent. A smooth curve was therefore drawn through these points and viscosities obtained, at intervals of 5° C, from 0° C to 80° C. Second differences were found to vary but slowly with temperature, so it was possible to extrapolate, with reasonable certainty, up to 100° C.

By using the calculated values of the viscosity μ and the values of C and k as given by equations (B3) and (B4), the Prandtl group was calculated from the definition $N_{Pr} = C\mu/k$ and a plot made of $\left(N_{Pr}\right)^{2/3}$ as a function of temperature. Vapor-pressure data were taken from references 16 and 17, interpolation being performed by plotting logarithm of pressure against reciprocals of absolute temperatures. Data on density were taken from the International Critical Tables (reference 15). Variation with temperature was found to be very nearly linear in the temperature range 0° C to 90° C. A summary of the pertinent data for liquid methanol is given in table IV.

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TABLE I.- SUMMARY OF WATER DATA AND RESULTS

Item	Run	28	29	30	33	34
1	W_c	8,020	8,210	774	768	8,180
2	t_{ci}	116.8	116.8	181.9	183.0	116.2
3	t_{co}	120.3	120.4	212.9	214.6	120.0
4	q_c	28,050	29,550	24,100	24,400	31,000
5	W_s	32.3	32.7	30.9	27.6	32.5
6	P	34.5	34.3	105.9	105.6	34.3
7	t_s	258.4	258.1	332.0	331.8	258.0
8	h_{fg}	938.6	938.5	884.3	884.5	938.5
9	q_L	730	720	1,275	1,320	660
10	q_{sc}	29,620	29,930	26,075	23,080	29,840
11	Deviation in heat balance $(q_{sc} - q_c)(100)/q_{sc}$, percent	5.3	1.3	7.6	-5.7	-3.9
12	Temperatures					
	A-1	141.8	141.9	244.7	253.3	141.9
	A-2	139.3	139.1	244.7	251.9	140.8
	A-3	141.3	141.4	245.7	253.2	142.3
	A-4	149.5	142.9	254.7	252.6	140.7
	B-1	145.3	146.1	241.5	264.1	144.4
	B-2	147.5	148.9	246.8	254.5	145.4
	B-3	146.3	145.5	242.7	254.2	144.6
	B-4	148.5	148.0	245.0	256.6	149.3
	C-1	160.0	160.3	246.2	259.2	164.7
	C-2	167.1	167.0	251.3	264.2	169.5
	C-3	162.4	163.6	249.5	263.7	166.0
	C-4	164.5	165.2	251.2	263.7	171.7
	D-1	172.7	173.2	251.5	263.3	171.2
	D-2	181.5	180.4	257.7	267.9	174.3
	D-3	174.2	177.8	257.1	268.2	176.0
	D-4	183.1	182.2	260.7	265.8	174.4
13	t_w	157.8	160.1	248.8	259.2	157.1
14	q_{av}/A_o	58,500	60,300	50,900	49,500	61,700
15	Δt_w	5.23	5.39	4.60	4.47	5.52
16	$1/h_d$	0	0	0.000006	0.0000016	0.000020
17	Δt_d	0	0	0.30	0.79	1.23
18	t_{li}	152.6	154.7	243.9	253.9	150.3
19	t_{li}(top)	172.7	183.0	251.3	261.0	167.2
20	P_l	27.4	28.7	15.4	20.2	28.7
21	t_{bp}	245.1	247.8	214.4	228.5	247.8
22	t_{ca}	118.6	118.6	197.4	198.8	118.1
23	h_c	1,780	1,720	1,130	126	1,980
24	G	1,184,000	1,212,000	114,000	113,300	1,208,000
25	V	5.33	5.46	0.527	0.523	5.44
26	$\left(\dfrac{\mu_w}{\mu_a}\right)^{0.14}$	0.960	0.958	0.964	0.958	0.962
27	$\left(N_{Pr}\right)^{2/3}$	2.39	2.39	1.50	1.49	2.40
28	j	0.00346	0.00326	0.01430	0.01170	0.00378
29	N_{Re}	25,100	26,000	4,500	4,500	25,800

TABLE I.- SUMMARY OF WATER DATA AND RESULTS - Continued

Item	Run	36	37	38	40	42
1	W_c	8,180	758	765	758	2,182
2	t_{ci}	116.1	181.3	181.0	180.3	168.1
3	t_{co}	119.7	210.5	206.9	203.3	180.3
4	q_c	29,400	22,250	19,800	17,430	26,600
5	W_s	31.8	25.4	23.2	22.2	30.0
6	P	34.3	102.6	104.4	104.5	102.8
7	t_s	258.1	329.7	331.0	331.0	329.8
8	h_{fg}	938.5	886.0	885.2	885.0	886.0
9	q_L	690	1,260	1,245	1,375	1,280
10	q_{sc}	29,160	21,290	19,200	18,255	25,300
11	Deviation in heat balance $(q_{sc} - q_c)(100)/q_{sc}$, percent	-0.8	-4.5	-3.1	4.5	-5.1
12	Temperatures					
	A-1	142.6	250.8	254.2	254.4	225.2
	A-2	139.2	247.8	251.0	251.3	221.1
	A-3	143.4	251.6	255.1	255.4	227.6
	A-4	143.6	252.4	255.3	256.4	228.3
	B-1	143.1	257.7	265.1	267.0	231.0
	B-2	148.1	254.3	260.6	265.2	239.6
	B-3	147.2	261.9	271.3	276.2	240.1
	B-4	151.2	259.7	264.6	278.3	243.0
	C-1	161.2	262.8	274.3	280.8	259.5
	C-2	176.2	267.3	278.2	283.8	263.8
	C-3	163.0	265.2	275.3	282.8	262.1
	C-4	168.5	266.7	277.5	285.0	265.0
	D-1	183.4	271.8	279.5	286.2	266.8
	D-2	182.6	271.1	278.9	286.7	267.9
	D-3	180.2	273.8	281.6	286.9	267.2
	D-4	182.7	274.1	281.0	288.5	268.0
13	t_w	159.7	261.8	268.9	274.1	248.5
14	q_{av}/A_o	59,400	44,300	39,600	36,200	52,600
15	Δt_w	5.31	4.01	3.58	3.27	4.75
16	$1/h_d = 0$	0.000026	0.000004	0.000008	0.000016	0.000024
17	$\Delta t_d = 0$	1.55	0.18	0.32	0.58	1.26
18	t_{li}	152.8	257.6	265.0	270.3	242.5
19	$t_{li}(top)$	175.5	268.5	276.3	283.3	261.5
20	P_l	26.2	27.4	33.9	38.8	25.4
21	t_{bp}	242.6	245.2	257.4	265.4	241.0
22	t_{ca}	117.9	195.9	194.0	191.8	174.2
23	h_c	1,760	740	575	476	796
24	G	1,207,000	112,000	113,000	111,800	322,000
25	V	5.43	0.517	0.521	0.515	1,473
26	$\left(\dfrac{\mu_w}{\mu_a}\right)^{0.14}$	0.959	0.953	0.946	0.941	0.943
27	$\left(N_{Pr}\right)^{2/3}$	2.40	1.51	1.53	1.54	1.68
28	j	0.00335	0.00951	0.00735	0.00616	0.00392
29	N_{Re}	25,700	4,360	4,330	4,220	10,820

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TABLE I.- SUMMARY OF WATER DATA AND RESULTS - Continued

Item	Run	43	44	45	46	47
1	W_c	2,208	2,158	1,766	8,180	5,110
2	t_{ci}	172.1	165.9	185.8	116.1	179.0
3	t_{co}	185.0	172.6	201.9	120.0	184.6
4	q_c	28,460	14,460	28,430	31,900	28,600
5	W_s	34.5	15.9	32.1	32.0	34.9
6	P	102.2	33.5	107.5	34.3	100.6
7	t_s	329.4	256.7	333.1	258.1	328.2
8	h_{fg}	886.0	939.0	883.4	938.5	887.3
9	q_L	1,300	700	1,280	630	1,240
10	q_{sc}	29.260	14.190	27,080	29,400	29,660
11	Deviation in heat balance $(q_{sc} - q_c)(100)/q_{sc}$, percent	2.7	-1.9	-5.0	-8.5	3.6
12	Temperatures					
	A-1	222.1	201.1	243.5	144.6	216.1
	A-2	217.8	198.8	239.8	140.8	211.7
	A-3	223.7	202.0	245.6	145.5	217.1
	A-4	225.5	202.7	246.9	146.2	218.1
	B-1	228.3	207.1	243.6	146.9	217.6
	B-2	235.1	210.6	247.1	152.1	223.1
	B-3	235.1	211.5	246.1	151.6	223.1
	B-4	238.0	210.8	251.5	154.7	226.1
	C-1	241.3	220.1	248.8	165.1	235.2
	C-2	245.6	222.8	255.2	171.0	240.3
	C-3	244.1	221.2	253.7	166.5	237.1
	C-4	247.0	224.2	254.5	172.5	242.4
	D-1	254.0	225.6	262.9	184.6	255.2
	D-2	252.3	226.2	261.8	183.5	253.8
	D-3	254.4	224.6	263.7	182.1	255.1
	D-4	254.0	225.9	263.1	182.6	255.7
13	t_w	238.7	214.7	251.8	161.9	233.0
14	q_{av}/A_o	58,550	29,050	56,300	61,000	59,100
15	Δt_w	5.28	2.61	5.08	5.45	5.32
16	$1/h_d$	0.000028	0.000043	0.000037	0.000041	0.000046
17	Δt_d	1.64	0.96	2.08	2.50	2.72
18	t_{li}	231.8	211.1	244.6	153.9	225.0
19	$t_{li}(top)$	246.9	222.0	255.7	175.2	247.0
20	P_l	15.8	20.2	19.1	26.7	19.0
21	t_{bp}	215.6	228.5	225.5	243.7	225.2
22	t_{ca}	178.6	169.2	193.8	118.0	181.8
23	h_c	1,135	715	1,142	1,754	1,410
24	G	326,000	319,000	261,000	1,208,000	755,000
25	V	1.495	1.458	1.202	5.44	3.46
26	$\left(\dfrac{\mu_w}{\mu_a}\right)^{0.14}$	0.955	0.962	0.959	0.958	0.963
27	$\left(N_{Pr}\right)^{2/3}$	1.65	1.73	1.52	2.40	1.62
28	j	0.00548	0.00374	0.00637	0.00334	0.00292
29	N_{Re}	11,300	10,340	10,020	25,700	26,700

TABLE I.- SUMMARY OF WATER DATA AND RESULTS - Continued

Item	Run	48	49	50	51	52
1	W_c	5,150	4,190	4,160	4,160	4,160
2	t_{ci}	179.1	189.4	189.1	188.6	187.8
3	t_{co}	185.4	195.9	195.6	194.8	194.2
4	q_c	32,400	27,250	27,040	25,800	26,650
5	W_s	34.4	32.4	31.8	31.2	32.8
6	P	100.6	100.2	98.7	100.7	100.7
7	t_s	328.2	328.0	326.9	328.3	328.3
8	h_{fg}	887.4	887.6	888.4	887.3	887.3
9	q_L	1,260	1,290	1,300	1,290	1,285
10	q_{sc}	29,290	27,460	26,900	26,360	27,760
11	Deviation in heat balance					
	$(q_{sc} - q_c)(100)/q_{sc}$, percent	-10.6	0.8	-0.5	2.1	4.1
12	Temperatures					
	A-1	218.5	228.0	228.0	229.1	227.9
	A-2	214.3	224.4	224.5	225.2	224.2
	A-3	220.7	230.3	230.0	230.6	230.6
	A-4	222.4	231.0	231.7	232.5	231.8
	B-1	220.3	229.9	231.5	232.1	230.2
	B-2	225.4	234.0	236.0	236.8	234.7
	B-3	225.5	234.2	235.8	237.1	234.8
	B-4	228.8	237.7	239.1	240.4	238.2
	C-1	239.2	244.8	244.3	250.4	244.8
	C-2	242.6	249.3	249.3	254.3	248.9
	C-3	240.3	246.9	247.2	252.1	246.0
	C-4	245.4	251.2	252.2	256.8	251.1
	D-1	255.8	259.0	260.3	266.0	259.6
	D-2	255.3	257.8	260.5	265.0	258.7
	D-3	255.3	258.7	261.3	264.7	259.3
	D-4	256.2	258.8	262.1	266.5	259.0
13	t_w	234.6	243.8	243.4	246.2	242.5
14	q_{av}/A_o	62,600	55,500	54,700	52,900	55,200
15	Δt_w	5.64	5.00	4.94	4.77	4.98
16	$1/h_d$	0.000051	0.000057	0.000062	0.000067	0.000072
17	Δt_d	3.19	3.16	3.39	3.54	3.94
18	t_{li}	225.8	235.6	235.1	237.9	233.5
19	$t_{li}(top)$	246.8	250.4	252.7	257.3	250.2
20	P_l	24.4	17.9	22.3	29.0	17.7
21	t_{bp}	238.7	222.0	233.8	248.4	221.5
22	t_{ca}	182.2	192.6	192.4	191.7	191.0
23	h_c	1,481	1,335	1,325	1,181	1,340
24	G	764,000	619,000	614,000	614,000	615,000
25	V	3.51	2.86	2.83	2.83	2.83
26	$\left(\dfrac{\mu_w}{\mu_a}\right)^{0.14}$	0.963	0.965	0.965	0.962	0.965
27	$(N_{Pr})^{2/3}$	1.62	1.53	1.54	1.54	1.55
28	j	0.00302	0.00318	0.00321	0.00286	0.00326
29	N_{Re}	27,100	23,550	23,300	23,200	23,200

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TABLE I.- SUMMARY OF WATER DATA AND RESULTS - Continued

Item	Run	53	54	56	57	59
1	W_c	8,180	4,170	4,160	8,660	8,220
2	t_{ci}	119.9	189.2	189.3	187.4	116.2
3	t_{co}	123.7	195.5	195.7	191.1	119.8
4	q_c	31,100	26,270	26,600	31,700	29,600
5	W_s	33.5	31.0	33.1	36.2	33.2
6	P	34.9	100.2	101.2	100.6	34.4
7	t_s	259.1	328.0	328.7	328.2	258.2
8	h_{fg}	937.8	887.6	887.0	887.4	938.3
9	q_L	760	1,280	1,290	1,260	690
10	q_{sc}	30,640	26,180	28,110	30,840	30,410
11	Deviation in heat balance $(q_{sc} - q_c)(100)/q_{sc}$, percent	-1.5	-0.3	5.4	-2.8	2.7
12	Temperatures					
	A-1	153.5	231.8	229.2	217.1	142.7
	A-2	149.4	228.0	225.1	213.0	140.1
	A-3	156.7	234.2	231.1	219.2	140.2
	A-4	157.5	235.8	232.5	220.2	143.0
	B-1	153.0	233.5	229.6	215.4	147.8
	B-2	158.0	239.0	234.4	219.3	148.6
	B-3	157.1	238.6	233.8	219.0	149.0
	B-4	161.0	242.4	238.1	223.0	150.6
	C-1	173.4	252.1	247.3	229.7	165.2
	C-2	177.9	256.3	252.0	235.0	167.5
	C-3	174.5	254.1	250.0	232.0	166.2
	C-4	179.5	259.5	254.3	237.3	167.9
	D-1	190.3	268.6	262.7	249.5	181.0
	D-2	190.4	267.3	262.7	247.7	182.9
	D-3	187.5	266.5	262.3	249.0	179.7
	D-4	187.5	268.0	262.9	249.2	179.8
13	t_w	169.2	248.5	244.2	229.7	159.5
14	q_{av}/A_o	62,700	53,200	55,500	63,400	60,900
15	Δt_w	5.62	4.80	5.00	5.71	5.45
16	$1/h_d$	0.000078	0.000083	0.000094	0.000099	0
17	Δt_d	4.89	4.41	5.21	6.27	0
18	t_{li}	158.7	239.3	234.0	217.7	154.1
19	$t_{li}(top)$	178.4	258.4	252.4	236.8	175.4
20	P_l	26.5	35.1	29.2	27.3	27.3
21	t_{bp}	243.3	259.4	248.8	245.0	245.0
22	t_{ca}	121.8	192.4	192.5	189.2	118.0
23	h_c	1,755	1,170	1,380	2,300	1,740
24	G	1,208,000	616,000	615,000	1,279,000	1,214,000
25	V	5.44	2.84	2.83	5.88	5.47
26	$\left(\dfrac{\mu_w}{\mu_a}\right)^{0.14}$	0.958	0.962	0.966	0.975	0.958
27	$\left(N_{Pr}\right)^{2/3}$	2.33	1.53	1.53	1.56	2.40
28	j	0.00324	0.00280	0.00331	0.00274	0.00329
29	N_{Re}	26,700	23,400	23,400	47,500	25,800

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TABLE I.- SUMMARY OF WATER DATA AND RESULTS - Continued

Item	Run	60	61	63	64	65
1	W_c	8,180	8,180	437	447	8,140
2	t_{ci}	117.0	116.9	105.1	107.6	116.8
3	t_{co}	120.5	120.9	140.0	181.1	120.8
4	q_c	28,600	32,700	15,240	32,850	32,560
5	W_s	34.6	37.8	17.3	38.9	38.3
6	P	34.5	34.5	34.4	68.2	34.1
7	t_s	258.4	258.4	258.2	301.2	257.8
8	h_{fg}	939.8	939.8	939.9	909.3	940.2
9	q_L	690	690	690	1,060	780
10	q_{sc}	31,810	34,810	15,540	34,340	35,220
11	Deviation in heat balance					
	$(q_{sc} - q_c)(100)/q_{sc}$, percent	10.2	6.1	1.9	4.3	7.6
12	Temperatures					
	A-1	143.2	148.4	220.7	259.7	169.1
	A-2	141.2	145.2	224.5	259.2	154.3
	A-3	140.9	145.1	219.3	255.4	155.4
	A-4	142.8	148.7	214.1	250.3	161.6
	B-1	147.6	148.0	218.1	239.9	148.6
	B-2	148.1	149.0	219.4	240.4	149.5
	B-3	148.6	149.3	219.4	239.4	149.7
	B-4	150.2	150.4	218.9	240.4	149.4
	C-1	164.7	165.8	246.8	258.7	162.8
	C-2	174.6	178.6	250.6	274.1	169.2
	C-3	165.4	167.6	247.2	263.8	166.1
	C-4	167.4	167.4	246.8	261.4	165.7
	D-1	192.6	203.6	241.2	259.7	196.9
	D-2	198.5	211.1	242.2	266.0	199.7
	D-3	188.2	212.1	245.0	270.9	203.0
	D-4	181.0	210.2	242.8	264.1	192.0
13	t_w	162.2	168.8	230.6	256.5	168.3
14	q_{av}/A_o	62,000	69,200	31,200	68,200	69,500
15	Δt_w	5.5	6.2	2.81	6.16	6.23
16	$1/h_d$	0.00001	0.00002	0.00003	0.00004	0
17	Δt_d	0.6	1.4	0.9	2.7	0
18	t_{li}	156.1	161.2	226.9	247.6	162.1
19	$t_{li}(top)$	184.0	201.6	239.1	256.3	191.7
20	P_l	27.6	28.2	15.9	16.6	26.3
21	t_{bp}	245.6	246.8	216.0	218.2	242.9
22	t_{ca}	118.8	118.9	122.6	144.4	118.8
23	h_c	1,720	1,690	308	682	1,660
24	G	1,208,000	1,208,000	64,600	66,000	1,203,000
25	V	5.44	5.44	0.291	0.299	5.42
26	$\left(\frac{\mu_v}{\mu_a}\right)^{0.14}$	0.957	0.952	0.901	0.911	0.951
27	$(N_{Pr})^{2/3}$	2.38	2.38	2.32	2.01	2.38
28	j	0.00324	0.00318	0.00999	0.01891	0.00312
29	N_{Re}	25,950	25,970	1,438	1,772	25,840

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TABLE I.- SUMMARY OF WATER DATA AND RESULTS - Continued

Item	Run	66	67	68	71	74
1	W_c	8,140	466	488	8,180	8,120
2	t_{ci}	116.0	141.4	91.8	116.3	115.2
3	t_{co}	119.3	167.6	117.9	120.2	118.8
4	q_c	26,860	12,210	12,740	31,900	29,230
5	W_s	33.9	13.7	14.0	34.6	33.9
6	P	34.4	35.4	24.7	34.4	34.5
7	t_s	258.2	259.9	239.4	258.2	258.4
8	h_{fg}	939.9	938.7	952.6	939.9	939.8
9	q_L	720	760	580	720	700
10	q_{cs}	31,080	12,100	12,790	31,780	31,150
11	Deviation in heat balance $(q_{sc} - q_c)(100)/q_{sc}$, percent	13.6	-0.9	0.4	-0.4	6.2
12	Temperatures					
	A-1	144.3	219.9	194.5	151.2	139.7
	A-2	144.3	217.5	190.6	147.9	140.5
	A-3	142.2	215.7	187.8	148.6	140.3
	A-4	143.4	218.2	191.1	157.5	141.1
	B-1	147.2	226.0	201.6	149.1	146.6
	B-2	148.4	226.3	202.0	150.1	147.7
	B-3	148.3	226.3	201.7	149.4	147.6
	B-4	148.8	226.6	201.7	150.2	149.0
	C-1	163.0	234.5	217.7	163.8	162.7
	C-2	167.2	235.6	218.5	168.8	166.1
	C-3	163.8	236.2	217.8	164.4	163.6
	C-4	165.5	236.5	218.4	166.8	166.5
	D-1	180.8	235.1	220.5	183.4	180.0
	D-2	180.7	235.6	220.5	183.0	181.5
	D-3	178.4	236.0	219.8	181.6	181.2
	D-4	177.5	236.6	220.7	180.3	177.6
13	t_w	159.0	228.9	207.8	162.3	158.2
14	q_{av}/A_o	58,800	24,660	25,880	64,600	61,200
15	Δt_w	5.26	2.22	2.32	5.78	5.48
16	$1/h_d$	0.000008	0.000012	0.000016	0.000024	0
17	Δt_d	0.47	0.30	0.41	1.55	0
18	t_{li}	153.3	226.4	205.1	155.0	152.7
19	$t_{li}(top)$	173.7	233.3	217.7	174.8	174.6
20	P_l	26.5	15.8	15.5	26.6	27.3
21	t_{bp}	243.3	215.6	214.6	243.5	245.0
22	t_{ca}	117.6	154.5	104.8	118.2	117.0
23	h_c	1,700	354	266	1,818	1,770
24	G	1,203,000	68,800	72,000	1,208,000	1,200,000
25	V	5.40	0.313	0.323	5.44	5.47
26	$\left(\dfrac{\mu_w}{\mu_a}\right)^{0.14}$	0.958	0.936	0.895	0.957	0.958
27	$(N_{Pr})^{2/3}$	2.41	1.88	2.65	2.40	2.42
28	j	0.00326	0.00905	0.00876	0.00345	0.00342
29	N_{Re}	25,560	2,000	1,348	25,800	25,350

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TABLE I.- SUMMARY OF WATER DATA AND RESULTS - Concluded

Item	Run	75	76	77	78	79
1	W_c	454	502	1,137	740	1,572
2	t_{ci}	90.7	87.5	93.9	89.7	140.9
3	t_{co}	140.7	111.7	110.3	108.6	151.6
4	q_c	22,700	12,150	18,630	13,980	16,820
5	W_s	25.5	13.1	20.6	15.2	18.5
6	P	61.2	21.6	34.6	28.5	33.5
7	t_{sc}	294.0	232.1	258.6	236.7	256.7
8	h_{fg}	914.5	957.4	939.6	954.4	940.9
9	q_L	1,020	460	700	500	680
10	q_{cs}	22,280	12,040	18,620	14,020	16,730
11	Deviation in heat balance $(q_{sc} - q_c)(100)/q_{sc}$, percent	-1.9	-0.9	-0.1	0.3	-0.5
12	Temperatures					
	A-1	192.9	166.5	162.0	158.9	183.4
	A-2	194.9	167.6	164.3	160.9	185.8
	A-3	194.9	167.6	164.6	161.1	185.9
	A-4	198.9	171.1	167.7	164.8	187.4
	B-1	221.5	193.7	193.4	189.2	202.7
	B-2	222.4	195.1	197.0	191.3	206.6
	B-3	222.9	194.5	198.8	191.4	207.1
	B-4	223.3	194.8	195.8	190.9	206.9
	C-1	244.3	212.3	226.9	216.3	236.7
	C-2	245.8	213.4	238.1	223.9	244.7
	C-3	245.5	213.5	237.5	224.5	245.0
	C-4	246.5	213.7	230.5	221.0	239.2
	D-1	249.1	214.2	225.0	215.9	227.1
	D-2	255.1	217.6	232.9	220.4	234.5
	D-3	268.5	221.7	242.2	225.7	241.5
	D-4	250.4	214.6	228.2	217.6	228.6
13	t_w	229.8	198.2	206.4	198.4	216.4
14	q_{av}/A_o	45,600	24,540	37,770	28,400	34,030
15	Δt_w	4.11	2.20	3.39	2.55	3.06
16	$1/h_d$	0.000008	0.000012	0.000016	0.000020	0.000024
17	Δt_d	0.36	0.29	0.60	0.57	0.82
18	t_{li}	225.3	195.7	202.4	195.3	212.5
19	$t_{li}(top)$	251.3	214.5	228.1	216.8	229.0
20	P_l	16.0	16.0	31.5	28.5	33.6
21	t_{bp}	216.3	216.3	253.2	247.4	256.9
22	t_{ca}	115.7	99.8	102.1	99.2	146.2
23	h_c	430	264.4	388.5	305.6	529
24	G	67,100	74,150	168,000	109,300	232,000
25	V	0.302	0.333	0.753	0.490	1.05
26	$\left(\dfrac{\mu_w}{\mu_a}\right)^{0.14}$	0.894	0.896	0.894	0.896	0.937
27	$\left(N_{Pr}\right)^{2/3}$	2.44	2.77	2.71	2.77	1.99
28	j	0.01400	0.00880	0.00560	0.00693	0.00426
29	N_{Re}	1,400	1,313	3,060	1,936	6,320

TABLE II.- SUMMARY OF METHANOL DATA AND RESULTS

Item	Run	81	83	85	86	87
1	W_c	5,810	5,960	3,146	1,792	1,786
2	t_{ci}	84.7	88.6	81.1	75.1	73.1
3	t_{co}	91.0	94.9	88.6	84.9	83.2
4	q_c	22,100	22,930	14,250	10,550	10,780
5	W_s	26.20	25.80	15.82	11.61	11.77
6	P	25.6	25.9	14.7	14.7	14.8
7	t_s	241.4	242.0	212.0	212.0	212.3
8	h_{fg}	951.2	950.8	970.2	970.2	970.0
9	q_L	600	550	340	550	530
10	q_{sc}	24,300	23,980	14,990	10,710	10,880
11	Deviation in heat balance $(q_{sc} - q_c)(100)/q_{sc}$, percent	9.1	4.3	4.9	1.5	0.9
12	Temperatures					
	A-1	140.3	143.5	143.8	154.6	154.1
	A-2	139.8	142.9	143.2	153.6	153.3
	A-3	135.8	139.0	139.0	150.2	149.6
	A-4	138.6	142.4	143.8	154.9	154.4
	B-1	157.9	160.7	165.0	179.6	179.6
	B-2	159.2	161.9	166.6	181.1	181.1
	B-3	158.4	161.2	165.6	180.3	180.5
	B-4	158.5	161.2	165.2	179.2	179.6
	C-1	178.3	180.3	179.2	193.2	193.2
	C-2	180.0	181.6	180.5	194.5	194.9
	C-3	177.3	179.1	179.0	194.4	194.3
	C-4	179.7	181.8	180.0	194.2	194.3
	D-1	191.1	194.0	181.0	188.6	188.4
	D-2	188.2	190.6	180.3	188.8	189.2
	D-3	186.8	189.3	179.6	188.4	188.7
	D-4	185.2	187.8	178.0	186.6	186.7
13	t_w	165.9	168.6	166.8	178.9	178.8
14	q_{av}/A_o	47,100	47,600	29,660	21,570	21,970
15	Δt_w	4.22	4.26	1.31	1.93	1.97
16	$1/h_d$					
17	Δt_d					
18	t_{li}	161.7	164.3	165.5	177.0	176.8
19	t_{li}(top)	183.6	186.1	178.4	192.2	192.2
20	P_l	31.5	30.0	41.8	40.8	48.4
21	t_{bp}	186.0	183.4	200.9	199.6	209.1
22	t_{ca}	87.8	91.8	84.8	80.0	78.2
23	h_c	627	645	362	218	219
24	G	859,000	881,000	465,000	265,000	263,600
25	V	4.90	5.04	2.65	1.50	1.49
26	$\left(\dfrac{\mu_w}{\mu_a}\right)^{0.14}$	0.931	0.932	0.924	0.911	0.909
27	$\left(N_{Pr}\right)^{2/3}$	3.391	3.350	3.422	3.475	3.496
28	J	0.00387	0.00374	0.00406	0.00435	0.00442
29	N_{Re}	20,560	21,720	10,860	5,970	5,850

TABLE II.- SUMMARY OF METHANOL DATA AND RESULTS - Continued

Item	Run	88	90	91	92	93
1	W_c	6,000	1,050	8,570	699	8,730
2	t_{ci}	87.5	75.6	92.8	81.8	99.3
3	t_{co}	94.1	88.4	97.7	97.5	104.0
4	q_c	24,160	8,085	25,800	6,510	25,440
5	W_s	26.06	8.90	28.60	7.24	27.84
6	P	25.4	14.9	26.3	14.8	26.1
7	t_s	241.0	212.7	242.9	212.4	242.4
8	h_{fg}	951.6	969.7	950.3	969.9	950.6
9	q_L	700	530	680	540	700
10	q_{sc}	24,100	8,095	26,520	6,470	25,750
11	Deviation in heat balance $(q_{sc} - q_c)(100)/q_{sc}$, percent	-0.2	0.1	2.7	-0.7	1.2
12	Temperatures					
	A-1	144.1	165.6	138.6	173.7	142.9
	A-2	143.4	165.1	138.5	173.5	142.7
	A-3	138.7	162.1	134.0	170.8	138.4
	A-4	142.3	166.7	136.8	174.7	141.4
	B-1	161.0	190.0	149.8	194.7	154.3
	B-2	162.7	191.3	152.1	195.8	155.5
	B-3	161.9	190.8	151.6	195.4	154.8
	B-4	161.7	189.9	152.0	194.6	154.8
	C-1	181.4	201.2	171.9	203.4	173.7
	C-2	183.0	202.5	173.8	204.3	175.3
	C-3	179.9	202.1	169.9	204.3	171.9
	C-4	183.2	202.1	173.3	204.3	174.9
	D-1	194.4	195.3	188.2	198.1	189.5
	D-2	191.8	196.4	185.5	199.4	186.4
	D-3	189.5	196.6	182.8	199.4	184.3
	D-4	187.8	194.9	181.0	197.8	182.1
13	t_w	169.2	188.3	161.2	192.8	164.0
14	q_{av}/A_o	48,950	16,430	53,000	13,180	51,900
15	Δt_w	4.39	1.47	4.74	1.17	4.64
16	$1/h_d$					
17	Δt_d					
18	t_{li}	164.8	186.8	156.5	191.6	159.4
19	t_{li}(top)	186.5	200.5	179.7	202.9	181.0
20	P_l	35.8	48.8	39.0	52.0	37.5
21	t_{bp}	192.6	209.6	197.2	213.5	195.1
22	t_{ca}	90.8	82.0	95.2	89.6	101.6
23	h_c	650	154.8	850	127.2	882
24	G	886,000	155,000	1,267,000	103,200	1,290,000
25	V	5.05	0.879	7.26	0.589	7.42
26	$\left(\dfrac{\mu_w}{\mu_a}\right)^{0.14}$	0.931	0.905	0.942	0.909	0.946
27	$\left(N_{Pr}\right)^{2/3}$	3.360	3.452	3.318	3.374	3.260
28	j	0.00376	0.00516	0.00342	0.00620	0.00340
29	N_{Re}	21,700	3,540	32,100	2,500	34,200

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TABLE II.- SUMMARY OF METHANOL DATA AND RESULTS - Continued

Item	Run	94	95	96	98	99
1	W_c	423	5,930	5,930	5,930	422
2	t_{ci}	100.0	86.9	86.8	89.5	100.5
3	t_{co}	118.8	92.1	91.2	96.2	119.2
4	q_c	4,890	18,800	15,830	24,240	4,960
5	W_s	5.68	19.47	15.99	26.35	5.72
6	P	14.9	14.9	14.8	27.1	14.8
7	t_s	212.7	212.7	212.4	244.5	212.4
8	h_{fg}	970.0	970.0	969.9	949.2	969.9
9	q_L	540	540	510	690	520
10	q_{sc}	4,960	18,350	15,010	24,310	5,030
11	Deviation of heat balance $(q_{sc} - q_c)(100)/q_{sc}$	1.4	-2.5	-5.5	0.3	1.4
12	Temperatures					
	A-1	184.6	129.6	100.6	145.8	185.0
	A-2	184.3	129.4	101.4	145.0	184.6
	A-3	182.1	125.4	99.5	140.0	182.1
	A-4	185.4	129.2	102.8	144.0	185.6
	B-1	200.7	146.5	138.3	163.4	201.1
	B-2	201.4	147.6	140.8	164.8	201.5
	B-3	201.2	147.0	139.5	163.6	201.2
	B-4	200.7	147.0	138.4	163.6	200.7
	C-1	205.7	162.9	159.9	183.4	205.8
	C-2	206.5	163.8	161.4	185.0	206.7
	C-3	206.7	161.6	159.4	182.3	206.7
	C-4	206.7	163.8	161.3	185.2	206.7
	D-1	201.3	174.7	170.9	196.5	201.1
	D-2	201.9	171.0	169.1	193.5	201.9
	D-3	202.6	169.3	169.2	191.1	202.6
	D-4	201.7	167.9	167.7	190.8	201.5
13	t_w	198.4	152.3	142.5	171.1	198.4
14	q_{av}/A_o	9,990	37,700	31,270	49,250	10,130
15	Δt_w	0.90	3.37	2.80	4.41	0.91
16	$1/h_d$					
17	Δt_d					
18	t_{li}	197.5	148.9	139.7	166.7	197.5
19	$t_{li}(top)$	205.5	167.3	166.4	188.6	205.6
20	P_l	51.2	34.4	37.9	38.8	50.9
21	t_{bp}	212.6	190.6	195.7	196.9	212.3
22	t_{ca}	109.4	89.5	89.0	92.8	109.8
23	h_c	111.7	625	606	655	113.6
24	G	62,500	879,000	876,000	875,000	62,300
25	V	0.362	5.02	4.99	5.00	0.360
26	$\left(\dfrac{\mu_v}{\mu_a}\right)^{0.14}$	0.924	0.943	0.950	0.931	0.924
27	$(N_{Pr})^{2/3}$	3.195	3.375	3.378	3.341	3.191
28	j	0.00840	0.00372	0.00366	0.00380	0.00856
29	N_{Re}	1,756	21,300	21,150	21,750	1,756

NACA

TABLE II.- SUMMARY OF METHANOL DATA AND RESULTS - Continued

Item	Run	100	101	103	104	105
1	W_c	6,140	5,970	6,000	426	426
2	t_{ci}	84.7	84.8	86.5	100.0	99.5
3	t_{co}	91.2	91.3	92.6	118.8	123.6
4	q_c	24,200	23,560	22,250	5,030	6,460
5	W_s	26.13	25.23	25.88	5.57	6.99
6	P	26.7	26.7	26.4	14.9	15.0
7	t_s	243.7	243.7	243.1	212.7	213.0
8	h_{fg}	949.7	949.7	950.2	969.6	969.4
9	q_L	640	610	660	500	530
10	q_{sc}	24,160	23,350	23,940	4,890	6,240
11	Deviation in heat balance					
	$(q_{sc} - q_c)(100)/q_{sc}$, percent	-0.2	-0.9	7.1	-2.9	-3.5
12	Temperatures					
	A-1	139.5	139.3	139.8	183.4	184.1
	A-2	139.6	139.7	136.9	181.6	182.3
	A-3	135.1	135.0	140.0	184.5	185.2
	A-4	137.5	137.3	139.9	184.1	185.0
	B-1	157.1	156.6	159.1	200.8	201.4
	B-2	158.8	159.6	160.7	201.7	202.1
	B-3	158.4	158.6	160.0	200.8	201.6
	B-4	156.9	156.6	160.7	200.8	201.6
	C-1	177.3	171.6	177.8	210.4	209.5
	C-2	184.2	179.4	178.7	211.1	210.2
	C-3	179.4	178.2	180.9	209.5	208.5
	C-4	174.0	172.5	183.4	210.2	209.5
	D-1	179.6	179.6	184.0	202.1	199.6
	D-2	184.5	183.7	183.2	202.8	200.1
	D-3	191.3	192.6	187.7	202.8	200.4
	D-4	174.9	175.3	183.6	201.2	198.7
13	t_w	164.2	163.4	166.0	199.2	198.8
14	q_{av}/A_o	49,050	47,600	46,800	10,060	12,880
15	Δt_w	4.39	4.26	4.19	0.90	1.16
16	$1/h_d$					
17	Δt_d					
18	t_{li}	159.8	159.1	161.8	198.3	197.6
19	t_{li}(top)	178.2	178.5	180.4	209.4	208.2
20	P_l	37.4	37.6	38.1	42.0	37.8
21	t_{bp}	195.0	195.2	196.0	201.1	195.5
22	t_{ca}	88.0	88.0	89.6	109.4	111.6
23	h_c	671	659	636	111.3	147.8
24	G	907,000	882,000	886,000	62,900	62,900
25	V	5.18	5.03	5.06	0.364	0.364
26	$\left(\dfrac{\mu_w}{\mu_a}\right)^{0.14}$	0.932	0.933	0.932	0.923	0.925
27	$\left(N_{Pr}\right)^{2/3}$	3.389	3.388	3.374	3.193	3.176
28	j	0.00386	0.00388	0.00372	0.00830	0.0109
29	N_{Re}	21,740	21,150	21,500	1,770	1,793

NACA

TABLE II.- SUMMARY OF METHANOL DATA AND RESULTS - Continued

Item	Run	106	107	108	109	110
1	W_c	426	426	427	426	425
2	t_{ci}	99.2	100.0	99.6	100.0	100.1
3	t_{co}	125.5	123.3	127.0	134.8	138.7
4	q_c	7,080	6,260	7,390	9,440	10,490
5	W_s	7.70	6.80	7.97	10.12	11.38
6	P	15.0	15.0	15.0	15.0	15.0
7	t_s	213.0	213.0	213.0	213.0	213.0
8	h_{fg}	969.5	969.5	969.5	969:5	969.5
9	q_L	530	530	530	530	530
10	q_{sc}	6,930	6,060	7,200	9,290	10,500
11	Deviation in heat balance $(q_{sc} - q_c)(100)/q_{sc}$, percent	-2.2	-3.3	-2.6	-1.6	0.1
12	Temperatures					
	A-1	183.2	183.4	183.2	182.1	180.0
	A-2	181.4	181.8	181.6	180.1	178.2
	A-3	184.1	184.5	184.4	182.7	180.1
	A-4	184.1	184.3	184.1	182.8	180.4
	B-1	200.3	200.8	199.9	195.3	190.0
	B-2	201.0	201.6	199.2	192.7	188.9
	B-3	200.5	201.0	199.3	192.9	188.6
	B-4	200.7	201.0	200.2	195.1	189.5
	C-1	207.8	209.5	208.2	204.4	203.5
	C-2	208.9	210.0	207.6	206.9	205.9
	C-3	206.8	208.7	206.7	202.6	201.0
	C-4	207.9	208.7	207.1	204.4	203.2
	D-1	198.2	197.2	197.6	195.8	194.2
	D-2	198.9	197.3	197.6	195.9	194.2
	D-3	199.1	197.7	198.4	197.2	195.4
	D-4	197.2	195.9	196.3	195.0	193.6
13	t_w	197.5	197.7	197.0	194.1	191.7
14	q_{av}/A_o	14,200	12,500	14,810	18,990	21,300
15	Δt_w	1.28	1.12	1.33	1.70	1.91
16	$1/h_d$					
17	Δt_d					
18	t_{11}	196.2	196.6	195.7	192.4	189.8
19	t_{11}(top)	206.5	208.1	206.1	202.9	201.5
20	P_1	34.3	31.7	28.4	25.6	22.6
21	t_{bp}	190.4	186.3	180.5	175.1	168.9
22	t_{ca}	112.4	111.6	113.3	117.4	119.4
23	h_c	166.8	145.2	176.3	248.5	298.6
24	G	62,900	62,900	63,100	62,900	62,800
25	V	0.364	0.364	0.366	0.366	0.366
26	$\left(\dfrac{\mu_w}{\mu_a}\right)^{0.14}$	0.928	0.926	0.929	0.935	0.939
27	$\left(N_{Pr}\right)^{2/3}$	3.169	3.175	3.160	3.129	3.115
28	f	0.01254	0.01074	0.01300	0.01820	0.02170
29	N_{Re}	1,807	1,791	1,822	1,870	1,891

TABLE II.- SUMMARY OF METHANOL DATA AND RESULTS - Continued

Item	Run	111	113	114	115	116
1	W_c	423	5,960	434	428	404
2	t_{ci}	100.2	84.9	101.5	101.0	102.0
3	t_{co}	143.5	91.4	137.8	142.9	150.9
4	q_c	11,760	23,530	10,080	11,510	12,790
5	W_s	12.62	26.40	10.52	12.28	13.86
6	P	15.0	26.9	14.8	24.7	24.8
7	t_s	213.0	244.2	212.3	239.4	239.6
8	h_{fg}	969.5	949.4	970.0	952.6	952.4
9	q_L	530	670	480	600	630
10	q_{sc}	11,710	24,390	9,720	11,100	12,570
11	Deviation in heat balance					
	$(q_{sc} - q_c)(100)/q_{sc}$, percent	-0.4	3.5	-3.7	-3.7	-1.8
12	Temperatures					
	A-1	178.0	139.5	178.7	199.9	195.8
	A-2	176.4	136.6	177.1	197.8	194.0
	A-3	178.0	139.8	178.5	199.6	195.4
	A-4	178.2	140.7	178.9	199.8	195.9
	B-1	185.2	160.0	185.5	210.9	204.1
	B-2	185.4	161.4	185.7	209.1	204.1
	B-3	185.2	160.7	185.7	207.3	203.7
	B-4	185.9	161.4	186.4	207.9	204.3
	C-1	202.4	178.7	191.8	214.2	210.2
	C-2	205.2	179.8	194.1	215.2	211.1
	C-3	200.0	181.2	192.7	214.7	210.6
	C-4	202.1	184.3	193.0	215.6	211.6
	D-1	192.7	183.6	192.4	216.0	212.4
	D-2	192.6	183.6	192.3	215.8	212.0
	D-3	194.4	187.2	194.0	216.7	213.3
	D-4	192.0	183.4	191.8	214.9	211.6
13	t_w	189.6	166.4	187.4	209.7	205.6
14	q_{av}/A_o	23,810	49,300	20,230	22,960	25,720
15	Δt_w	2.14	4.41	1.82	2.06	2.31
16	$1/h_d$					
17	Δt_d					
18	t_{li}	187.5	162.0	185.6	207.6	203.3
19	$t_{li}(top)$	200.3	180.1	191.1	213.7	210.0
20	P_l	19.7	39.3	19.3	34.1	28.1
21	t_{bp}	162.1	197.7	161.0	190.2	179.9
22	t_{ca}	121.8	88.2	119.6	122.0	126.4
23	h_c	356.4	656	302.8	264.0	330.0
24	G	62,500	881,000	64,100	63,200	59,600
25	V	0.364	5.03	0.373	0.369	0.349
26	$\left(\dfrac{\mu_w}{\mu_a}\right)^{0.14}$	0.942	0.930	0.942	0.928	0.936
27	$(N_{Pr})^{2/3}$	3.097	3.386	3.114	3.095	3.064
28	j	0.02600	0.00386	0.0216	0.0187	0.0246
29	N_{Re}	1,914	21,160	1,933	1,942	1,887

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TABLE II.- SUMMARY OF METHANOL DATA AND RESULTS - Continued

Item	Run	117	118	121	122	123
1	W_c	406	396	1,048	1,043	1,047
2	t_{ci}	101.3	101.3	97.2	97.4	98.3
3	t_{co}	154.9	155.8	117.9	116.2	114.9
4	q_c	14,120	14,020	13,590	12,290	10,870
5	W_s	15.46	15.87	15.32	14.37	12.23
6	P	24.8	24.5	26.6	26.4	26.5
7	t_s	239.6	239.0	243.5	243.0	243.3
8	h_{fg}	952.4	952.9	949.8	950.1	949.9
9	q_L	640	630	660	650	650
10	q_{sc}	14,080	14,490	13,890	13,000	10,970
11	Deviation in heat balance $(q_{sc} - q_c)(100)/q_{sc}$, percent	-0.3	3.2	2.2	5.5	0.9
12	Temperatures					
	A-1	191.1	189.0	190.0	190.5	192.4
	A-2	189.5	187.0	187.2	187.7	189.7
	A-3	190.8	188.4	190.8	191.5	193.6
	A-4	191.5	189.1	191.3	191.8	193.8
	B-1	198.7	195.8	207.7	211.1	217.0
	B-2	198.5	195.8	206.8	211.1	218.3
	B-3	198.5	195.8	206.6	210.2	217.9
	B-4	199.4	196.7	210.7	211.6	217.9
	C-1	206.6	204.1	211.5	214.7	219.9
	C-2	207.3	204.8	212.5	215.6	220.5
	C-3	207.1	204.8	212.0	215.8	220.3
	C-4	208.2	205.7	213.1	216.3	222.4
	D-1	208.9	206.4	210.2	212.4	216.3
	D-2	208.6	206.1	210.2	212.5	216.9
	D-3	210.4	208.2	211.3	213.4	216.9
	D-4	208.0	205.2	210.4	212.7	216.1
13	t_w	201.5	199.0	205.2	207.5	211.9
14	q_{av}/A_o	28,600	28,920	27,900	25,640	22,160
15	Δt_w	2.57	2.60	2.50	2.30	1.99
16	$1/h_d$					
17	Δt_d					
18	t_{li}	198.9	196.4	202.7	205.2	209.9
19	$t_{li}(top)$	206.4	203.9	209.8	213.3	218.8
20	P_l	23.2	20.2	29.0	33.9	40.2
21	t_{bp}	170.1	163.2	181.6	189.8	198.8
22	t_{ca}	128.1	128.6	107.6	106.8	106.6
23	h_c	396	420	288.6	256.8	211.4
24	G	60,000	58,500	154,800	154,100	154,700
25	v	0.352	0.343	0.894	0.889	0.893
26	$\left(\dfrac{\mu_w}{\mu_a}\right)^{0.14}$	0.940	0.942	0.919	0.916	0.913
27	$\left(N_{Pr}\right)^{2/3}$	3.052	3.048	3.208	3.214	3.216
28	j	0.0294	0.0318	0.00877	0.00785	0.00641
29	N_{Re}	1,922	1,880	4,290	4,250	4,260

TABLE II.- SUMMARY OF METHANOL DATA AND RESULTS - Continued

Item		Run	124	125	126	127	128
1	W_c		6,000	1,050	1,049	1,050	1,051
2	t_{ci}		86.1	100.1	95.7	94.1	85.6
3	t_{co}		92.5	114.9	118.4	119.1	102.6
4	q_c		23,360	9,740	14,930	16,420	10,970
5	W_s		26.26	11.19	16.57	18.21	12.02
6	P		26.8	26.6	27.0	26.7	26.8
7	t_s		243.9	243.5	244.3	243.7	243.9
8	h_{fg}		949.6	949.9	949.3	949.7	949.6
9	q_L		670	660	670	660	660
10	q_{sc}		24,250	9,960	15,060	16,640	10,760
11	Deviation in heat balance						
	$(q_{sc} - q_c)(100)/q_{sc}$, percent		3.7	2.2	0.9	1.3	-2.0
12	Temperatures						
	A-1		140.5	194.0	187.7	183.0	188.6
	A-2		138.2	191.1	185.0	180.5	185.4
	A-3		141.1	194.7	187.7	182.8	189.5
	A-4		142.3	194.9	188.4	183.6	189.5
	B-1		160.5	219.2	203.7	195.3	216.7
	B-2		161.8	219.9	201.7	194.9	217.9
	B-3		161.2	219.2	201.0	195.1	216.9
	B-4		160.2	219.7	202.1	195.6	217.2
	C-1		178.9	227.5	208.4	202.5	224.2
	C-2		179.6	225.0	208.9	203.2	224.2
	C-3		181.9	227.7	208.8	203.2	224.8
	C-4		184.6	229.3	210.0	204.6	224.6
	D-1		183.9	220.5	209.7	205.2	218.1
	D-2		183.6	219.7	209.3	204.6	218.5
	D-3		187.0	219.7	211.5	206.2	219.4
	D-4		183.2	217.9	208.4	204.6	216.9
13	t_w		166.8	215.0	202.0	196.6	212.1
14	q_{av}/A_o		48,300	19,980	30,430	33,530	22,030
15	Δt_w		4.32	1.80	2.73	3.01	1.98
16	$1/h_d$						
17	Δt_d						
18	t_{li}		162.5	213.2	199.3	193.6	210.1
19	t_{li}(top)		180.1	225.6	207.0	202.2	222.5
20	P_l		37.3	46.5	24.3	18.8	50.4
21	t_{bp}		194.9	206.8	172.5	159.8	211.7
22	t_{ca}		89.3	107.5	107.0	106.6	94.1
23	h_c		649	186.0	323.7	378.4	186.5
24	G		886,000	155,100	155,000	155,100	155,200
25	V		5.06	0.896	0.896	0.894	0.888
26	$\left(\dfrac{\mu_w}{\mu_a}\right)^{0.14}$		0.931	0.912	0.921	0.924	0.901
27	$(N_{Pr})^{2/3}$		3.376	3.208	3.212	3.216	3.328
28	j		0.00378	0.00559	0.00990	0.01162	0.00487
29	N_{Re}		21,430	4,300	4,280	4,270	3,900

TABLE II.- SUMMARY OF METHANOL DATA AND RESULTS - Continued

Item	Run	129	130	131	132	133
1	W_c	1,050	2,960	2,954	2,975	2,960
2	t_{ci}	95.0	94.8	95.2	95.5	95.5
3	t_{co}	123.1	103.6	104.0	104.2	104.9
4	q_c	18,530	16,100	16,080	16,080	17,260
5	W_s	20.44	18.35	18.34	18.12	19.41
6	P	29.2	26.8	27.1	26.5	26.4
7	t_s	248.8	243.9	244.6	243.3	243.0
8	h_{fg}	946.3	949.6	949.1	950.0	950.1
9	q_L	680	680	650	640	640
10	q_{sc}	18,660	16,740	16,750	16,580	17,780
11	Deviation in heat balance $(q_{sc} - q_c)(100)/q_{sc}$, percent	0.7	3.8	4.0	3.1	2.9
12	Temperatures					
	A-1	182.3	165.9	166.8	166.1	165.6
	A-2	180.0	162.7	163.8	163.4	162.5
	A-3	182.1	166.6	167.7	167.0	166.8
	A-4	182.7	167.4	168.3	167.7	167.0
	B-1	193.1	191.5	192.6	191.8	190.6
	B-2	193.1	193.3	194.0	193.3	192.2
	B-3	193.1	192.0	193.1	192.2	191.5
	B-4	194.0	192.4	193.5	192.6	191.8
	C-1	201.0	206.2	207.0	205.7	199.9
	C-2	201.6	207.5	208.4	207.3	199.6
	C-3	201.6	207.7	208.4	207.3	202.1
	C-4	203.4	208.2	209.5	208.8	203.2
	D-1	204.1	203.7	205.7	203.9	199.6
	D-2	203.4	204.4	205.9	204.4	199.0
	D-3	205.7	206.1	207.7	206.1	200.8
	D-4	202.6	202.8	205.0	203.5	198.1
13	t_w	195.2	192.4	193.6	192.6	189.4
14	q_{av}/A_o	37,730	33,310	33,310	33,120	35,540
15	Δt_w	3.39	2.99	2.99	2.97	3.19
16	$1/h_d$					
17	Δt_d					
18	t_{li}	191.8	189.4	190.6	189.6	186.2
19	$t_{li}(top)$	200.6	204.4	205.3	204.3	199.0
20	P_l	16.4	28.8	33.8	23.7	17.8
21	t_{bp}	153.1	181.3	189.6	171.2	157.0
22	t_{ca}	109.0	99.2	99.6	99.8	100.2
23	h_c	448	363.3	360.0	362.7	406
24	G	155,200	437,000	436,000	439,000	437,000
25	V	0.897	2.51	2.50	2.52	2.51
26	$\left(\dfrac{\mu_w}{\mu_a}\right)^{0.14}$	0.928	0.920	0.920	0.921	0.924
27	$(N_{Pr})^{2/3}$	3.195	3.280	3.278	3.276	3.271
28	j	0.01368	0.00405	0.00402	0.00402	0.00453
29	N_{Re}	4,350	11,380	11,400	11,500	11,490

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TABLE II.- SUMMARY OF METHANOL DATA AND RESULTS - Continued

Item	Run	134	135	136	137	138
1	W_c	2,952	2,980	2,961	6,000	5,520
2	t_{ci}	97.2	94.1	91.7	88.6	112.8
3	t_{co}	108.0	107.2	106.3	95.0	118.6
4	q_c	19,810	24,220	26,790	23,400	20,250
5	W_s	22.81	27.40	31.06	26.23	22.65
6	P	33.3	44.7	55.4	26.7	27.0
7	t_s	256.4	274.0	201.5	243.7	244.3
8	h_{fg}	941.2	928.9	919.3	949.7	949.3
9	q_L	750	840	930	660	660
10	q_{sc}	20,720	24,560	27,510	24,250	20,820
11	Deviation in heat balance $(q_{sc} - q_c)(100)/q_{sc}$, percent	4.4	1.4	3.0	3.5	2.7
12	Temperatures					
	A-1	172.2	176.2	179.4	142.7	160.7
	A-2	167.2	172.4	175.5	140.0	158.4
	A-3	173.3	177.3	180.1	142.9	160.7
	A-4	174.2	178.2	181.2	144.1	162.0
	B-1	199.0	202.6	200.5	162.3	176.9
	B-2	199.9	202.6	201.2	163.4	177.8
	B-3	199.0	201.7	202.8	162.9	177.1
	B-4	199.8	201.7	201.4	163.8	177.8
	C-1	205.2	204.6	206.6	180.7	190.6
	C-2	202.5	206.1	208.2	181.2	191.3
	C-3	202.6	206.2	207.7	182.8	192.4
	C-4	207.3	209.1	210.9	186.4	194.0
	D-1	205.9	210.4	213.1	185.5	196.0
	D-2	205.2	209.7	212.5	185.5	195.6
	D-3	207.5	212.7	215.8	189.1	199.0
	D-4	204.6	209.1	211.8	184.5	194.7
13	t_w	195.3	198.8	200.6	168.6	181.6
14	q_{av}/A_o	41,100	49,470	55,200	48,320	41,660
15	Δt_w	3.69	4.44	4.96	4.32	3.74
16	$1/h_d$					
17	Δt_d					
18	t_{li}	191.6	194.4	195.6	164.3	177.9
19	$t_{li}(top)$	202.1	206.1	208.3	181.9	192.6
20	P_l	18.9	19.1	19.0	37.8	27.9
21	t_{bp}	160.0	160.5	160.2	195.5	179.6
22	t_{ca}	102.6	100.6	99.0	91.8	115.7
23	h_c	455	519	561	655	659
24	G	436,000	440,000	438,000	886,000	815,000
25	V	2.51	2.53	2.51	5.06	4.73
26	$\left(\dfrac{\mu_w}{\mu_a}\right)^{0.14}$	0.922	0.918	0.916	0.932	0.945
27	$\left(N_{Pr}\right)^{2/3}$	3.250	3.268	3.282	3.351	3.143
28	j	0.00502	0.00571	0.00624	0.00378	0.00378
29	N_{Re}	11,660	11,600	11,410	21,850	23,940

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TABLE II.- SUMMARY OF METHANOL DATA AND RESULTS - Concluded

Item	Run	139	140	141	142	143	144
1	W_c	5,520	5,520	5,485	5,485	5,520	2,965
2	t_{ci}	113.2	113.2	113.8	114.7	115.0	91.9
3	t_{co}	118.8	119.3	120.6	122.5	124.0	109.6
4	q_c	19,610	21,500	23,820	27,200	31,750	32,570
5	W_s	22.65	24.82	27.27	30.86	37.10	38.40
6	P	26.9	34.5	42.9	56.0	83.0	83.0
7	t_s	244.3	258.2	271.6	288.2	314.6	314.6
8	h_{fg}	949.3	939.8	929.3	918.8	899.1	899.1
9	q_L	660	750	840	940	1,170	1,170
10	q_{sc}	20,820	22,600	24,500	27,420	32,150	33,340
11	Deviation in heat balance $(q_{sc} - q_c)(100)/q_{sc}$, percent	5.8	4.9	2.8	0.8	1.2	2.3
12	Temperatures						
	A-1	160.9	165.0	169.9	175.5	183.4	186.6
	A-2	158.9	162.5	167.7	172.6	180.7	183.8
	A-3	161.1	165.2	170.2	175.5	183.9	186.6
	A-4	162.0	166.3	171.5	177.0	185.4	188.4
	B-1	177.1	182.3	188.6	195.4	205.2	199.8
	B-2	178.3	183.9	190.0	196.5	206.6	200.2
	B-3	177.4	183.2	189.1	195.7	205.7	200.0
	B-4	178.0	183.9	190.0	196.2	206.6	201.6
	C-1	190.9	198.3	205.5	210.0	215.2	209.7
	C-2	191.7	199.6	207.0	211.1	216.9	214.3
	C-3	192.6	200.1	207.7	211.8	218.3	212.2
	C-4	194.9	202.6	210.2	214.7	219.6	215.1
	D-1	195.8	204.4	212.7	216.9	224.6	220.2
	D-2	195.4	204.4	212.7	216.1	223.2	218.7
	D-3	199.0	207.5	215.4	219.6	227.3	223.6
	D-4	194.5	203.7	211.1	215.2	221.9	219.5
13	t_w	181.8	188.3	195.0	200.0	207.8	205.0
14	q_{av}/A_o	41,020	44,800	49,000	55,400	64,800	66,900
15	Δt_w	3.68	4.02	4.40	4.97	5.83	6.01
16	$1/h_d$						
17	Δt_d						
18	t_{li}	178.1	184.3	190.6	195.0	202.0	199.0
19	t_{li}(top)	192.5	201.0	208.6	212.0	218.4	214.5
20	P_l	23.0	23.1	23.3	23.1	23.1	19.2
21	t_{bp}	169.7	170.0	170.3	170.0	170.0	160.7
22	t_{ca}	116.0	116.2	117.2	118.6	119.5	100.8
23	h_c	650	646	658	714	771	670
24	G	815,000	815,000	810,000	810,000	815,000	438,000
25	V	4.73	4.73	4.71	4.71	4.74	2.52
26	$\left(\dfrac{\mu_w}{\mu_a}\right)^{0.14}$	0.945	0.940	0.936	0.934	0.930	0.915
27	$(N_{Pr})^{2/3}$	3.140	3.138	3.130	3.121	3.114	3.266
28	j	0.00374	0.00368	0.00374	0.00403	0.00430	0.00739
29	N_{Re}	24,000	24,100	24,040	24,280	24,570	11,570

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TABLE III.- SUMMARY OF DATA AND RESULTS; METHANOL WITH ENTRAINED AIR

Item	Run	145	145A	145B	145C	146
1	W_c	5,520	5,505	5,520	5,500	2,572
2	t_{c1}	93.2	93.6	93.7	93.7	83.1
3	t_{co}	98.4	98.9	99.2	99.1	91.4
4	q_c	17,680	18,050	18,770	18,360	12,600
5	W_s	18.97	19.79	19.97	20.56	13.74
6	P	14.9	14.9	15.0	14.9	14.9
7	t_s	212.7	212.7	213.0	212.7	212.7
8	h_{fg}	969.6	969.6	969.6	969.6	969.7
9	q_L	540	540	540	540	550
10	q	17,840	18,660	18,800	19,380	12,770
11	Deviation in heat balance					
	$(q_{sc} - q_c)(100)/q_{sc}$, percent	0.9	3.3	0.2	5.3	1.3
12	Temperatures					
	A-1	137.3	137.8	137.0	136.4	149.2
	A-2	135.5	135.7	135.5	134.6	146.8
	A-3	137.3	137.9	137.2	136.4	149.9
	A-4	138.2	138.4	138.4	137.3	150.8
	B-1	153.3	152.5	151.4	148.8	173.1
	B-2	154.6	153.8	152.1	149.2	174.6
	B-3	154.0	153.0	151.5	149.0	173.2
	B-4	154.4	153.7	152.1	149.5	174.2
	C-1	166.5	165.2	164.1	161.6	185.9
	C-2	167.7	166.3	165.1	162.5	187.5
	C-3	168.8	167.5	166.3	164.3	187.2
	C-4	170.6	169.4	168.6	166.6	188.1
	D-1	171.5	170.2	170.1	168.6	182.3
	D-2	171.0	169.5	169.2	167.2	183.0
	D-3	174.4	173.1	172.4	170.6	184.1
	D-4	172.4	170.7	170.6	168.6	183.0
13	t_w	158.0	157.2	156.4	154.5	173.3
14	q_{av}/A_o	36,020	37,240	38,100	38,300	25,730
15	Δt_w	3.22	3.33	3.41	3.42	2.30
16	$1/h_d$					
17	Δt_d					
18	t_{li}	154.8	153.9	153.0	151.1	171.0
19	t_{li}(top)	169.1	167.6	167.2	165.4	184.9
20	P_l	23.2	23.2	23.6	24.4	27.0
21	t_{bp}	170.2	170.2	171.0	172.7	177.9
22	t_{ca}	95.8	96.2	96.4	96.4	87.4
23	h_c	600	634	661	688	302.8
24	G	815,000	813,000	816,000	813,000	380,000
25	V	4.67	4.66	4.68	4.66	2.16
26	$\left(\dfrac{\mu_w}{\mu_a}\right)^{0.14}$	0.944	0.945	0.946	0.948	0.923
27	$(N_{Pr})^{2/3}$	3.312	3.308	3.307	3.307	3.396
28	J	0.00376	0.00397	0.00411	0.00431	0.00411
29	N_{Re}	20,700	20,750	20,850	20,780	9,050
30	W_a	0	0.1547	0.464	1.258	0
31	Q_a	0	1.678	4.93	12.82	0
32	Air, percent	0	1.46	4.16	10.16	0

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TABLE III.- SUMMARY OF DATA AND RESULTS; METHANOL WITH ENTRAINED AIR - Continued

Item	Run	146A	146B	146C	147	147A
1	W_c	2,586	2,564	.2,557	1,037	1,037
2	t_{c1}	83.2	82.4	82.9	73.8	74.3
3	t_{co}	92.1	92.3	93.5	86.9	89.7
4	q_c	13,190	15,380	16,440	8,140	9,610
5	W_s	14.92	16.45	17.95	8.88	10.60
6	P	14.9	15.0	14.9	15.1	14.9
7	t_s	212.7	213.0	212.7	213.4	212.7
8	h_{fg}	969.7	969.5	969.6	969.4	969.7
9	q_L	540	550	540	540	530
10	q	13,930	15,400	16,860	8,070	9,750
11	Deviation in heat balance					
	$(q_{sc} - q_c)(100)/q_{sc}$, percent	5.3	0.1	2.5	-0.8	1.4
12	Temperatures					.
	A-1	147.7	144.0	141.6	165.2	155.7
	A-2	144.0	141.3	139.3	162.3	153.1
	A-3	147.6	144.0	142.0	166.1	156.7
	A-4	148.6	145.4	142.9	166.1	157.5
	B-1	170.1	162.9	157.5	190.6	184.5
	B-2	170.3	163.8	157.9	191.8	187.2
	B-3	169.7	163.4	157.3	190.9	185.9
	B-4	170.4	164.5	158.0	191.2	185.8
	C-1	181.9	177.3	172.2 -	202.3	195.4
	C-2	182.5	178.7	172.4	203.0	198.1
	C-3	183.1	179.2	173.3	202.6	197.1
	C-4	184.3	181.0	175.3	203.0	197.1
	D-1	180.6	179.1	174.2	195.8	190.2
	D-2	180.6	179.2	173.7	196.9	194.0
	D-3	182.7	181.6	176.7	196.5	193.5
	D-4	181.3	180.3	175.6	195.3	190.6
13	t_w	170.4	166.6	161.8	188.7	182.7
14	q_{av}/A_o	27,500	31,200	33,780	16,440	19,640
15	Δt_w	2.46	2.79	3.02	1.47	1.76
16	$1/h_d$					
17	Δt_d					
18	t_{li}	167.9	163.8	158.8	187.2	180.9
19	t_{li}(top)	180.5	177.2	172.0	201.2	195.1
20	P_l	27.0	27.2	27.2	39.5	39.8
21	t_{bp}	177.9	178.2	178.2	197.9	198.3
22	t_{ca}	87.6	87.4	88.2	80.4	82.0
23	h_c	337.4	401	470	151.4	195.2
24	G	382,300	379,200	378,000	153,200	153,200
25	V	2.18	2.16	2.16	0.869	0.870
26	$\left(\dfrac{\mu_w}{\mu_a}\right)^{0.14}$	0.925	0.928	0.933	0.903	0.910
27	$(N_{Pr})^{2/3}$	3.393	3.396	3.387	3.470	3.452
28	j	0.00455	0.00549	0.00649	0.00515	0.00665
29	N_{Re}	9,130	9,030	9,060	3,462	3,504
30	W_a	0.1552	0.466	1.470	0	0.0965
31	q_a	1.330	3.96	12.48	0	0.523
32	Air, percent	2.46	6.99	19.22	0	2.41

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TABLE III.- SUMMARY OF DATA AND RESULTS; METHANOL WITH ENTRAINED AIR - Continued

Item	Run	147B	148	148A	148B	148C
1	W_c	1,048	5,471	5,330	5,370	5,340
2	t_{ci}	75.8	113.4	113.5	114.3	114.2
3	t_{co}	94.4	122.6	123.1	123.8	123.7
4	q_c	11,890	32,170	32,600	32,440	32,360
5	W_s	12.39	36.90	37.00	37.80	37.90
6	P	14.9	83.1	83.0	83.0	83.0
7	t_s	212.7	314.7	314.6	314.6	314.6
8	h_{fg}	969.6	899.1	899.1	899.1	899.1
9	q_L	520	1,130	1,120	1,110	1,110
10	q	11,490	32,050	32,140	32,890	32,970
11	Deviation in heat balance					
	$(q_{sc} - q_c)(100)/q_{sc}$, percent	-3.5	-0.4	-1.4	1.4	1.9
12	Temperatures					
	A-1	153.2	184.1	183.3	183.4	181.4
	A-2	151.8	181.4	180.3	180.7	178.3
	A-3	154.6	184.5	184.0	183.4	181.4
	A-4	155.1	185.0	185.6	185.2	183.2
	B-1	177.0	206.6	205.0	201.9	197.2
	B-2	181.2	207.0	205.9	202.1	197.2
	B-3	179.4	206.4	205.0	201.6	196.9
	B-4	179.8	207.7	206.3	203.0	197.8
	C-1	186.2	218.8	218.7	217.6	216.4
	C-2	189.0	220.6	220.6	219.0	217.4
	C-3	188.4	220.8	220.8	219.2	217.6
	C-4	189.1	223.5	224.1	222.8	221.4
	D-1	184.8	228.2	228.6	227.7	227.5
	D-2	186.4	226.9	227.3	226.5	225.7
	D-3	188.5	230.9	231.8	230.7	230.0
	D-4	187.6	225.1	225.9	225.4	224.8
13	t_w	174.5	209.9	209.6	208.2	205.9
14	q_{av}/A_o	23,720	65,100	65,660	66,250	66,250
15	Δt_w	2.13	5.86	5.96	5.95	5.95
16	$1/h_d$					
17	Δt_d					
18	t_{li}	172.4	204.0	203.6	202.2	199.9
19	t_{li}(top)	184.7	221.9	222.4	221.6	221.0
20	P_l	40.2	23.3	23.3	23.3	23.9
21	t_{bp}	198.8	170.4	170.4	170.4	171.7
22	t_{ca}	85.1	118.0	118.3	119.0	119.0
23	h_c	267.8	745	759	783	805
24	G	155,000	808,000	787,000	794,000	789,000
25	V	0.882	4.69	4.58	4.62	4.59
26	$\left(\dfrac{\mu_y}{\mu_a}\right)^{0.14}$	0.919	0.927	0.928	0.929	0.931
27	$\left(N_{Pr}\right)^{2/3}$	3.418	3.125	3.122	3.118	3.118
28	j	0.00895	0.00420	0.00437	0.00449	0.00465
29	N_{Re}	3,632	24,120	23,570	23,880	23,720
30	W_a	0.3488	0	0.1468	0.476	1.197
31	Q_a	1.898	0	1.958	6.38	15.39
32	Air, percent	8.13	0	1.724	5.36	12.08

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TABLE III.- SUMMARY OF DATA AND RESULTS; METHANOL WITH ENTRAINED AIR - Continued

Item	Run	149	149A	149B	149C	150
1	W_c	2,761	2,761	2,761	2,752	954
2	t_{ci}	92.3	92.7	92.1	91.0	103.0
3	t_{co}	110.3	110.8	110.2	109.6	125.3
4	q_c	30,370	31,030	30,980	31,730	13,470
5	W_s	36.69	36.89	37.01	37.68	14,83
6	P	83.1	83.1	83.1	82.6	26.8
7	t_s	314.7	314.7	314.7	314.2	243.9
8	h_{fg}	899.0	899.0	899.0	899.4	949.5
9	q_L	1,150	1,140	1,130	1,140	680
10	q	31,830	32,020	32,140	32,750	13,400
11	Deviation in heat balance $(q_{sc} - q_c)(100)/q_{sc}$, percent	4.6	3.1	3.6	3.1	-0.5
12	Temperatures					
	A-1	191.8	190.8	186.4	182.1	191.3
	A-2	187.9	186.6	182.3	178.9	189.1
	A-3	192.4	190.6	185.9	182.5	191.5
	A-4	193.3	192.2	188.4	185.0	192.0
	B-1	208.4	207.6	205.7	202.0	205.3
	B-2	208.0	206.7	205.2	202.1	205.3
	B-3	207.3	206.5	204.7	201.6	205.0
	B-4	208.9	208.0	206.6	203.7	205.9
	C-1	220.6	220.3	219.6	218.3	213.4
	C-2	221.9	221.5	220.8	219.7	214.3
	C-3	221.5	221.5	221.0	219.9	214.7
	C-4	224.6	224.6	224.2	223.7	215.8
	D-1	228.9	229.1	228.7	228.2	215.4
	D-2	227.8	227.8	227.3	226.9	216.0
	D-3	231.8	232.2	232.0	231.1	217.4
	D-4	226.4	226.6	226.4	225.7	215.1
13	t_w	212.6	212.1	210.4	208.2	206.8
14	q_{av}/A_o	63,100	64,000	64,000	65,400	27,270
15	Δt_w	5.67	5.76	5.75	5.87	2.45
16	$1/h_d$					
17	Δt_d					
18	t_{li}	206.9	206.3	204.6	202.3	204.4
19	t_{li}(top)	223.0	223.1	222.8	222.1	213.6
20	P_l	23.8	24.6	24.7	24.2	24.4
21	t_{bp}	171.4	173.1	173.4	172.3	172.7
22	t_{ca}	101.3	101.8	101.2	100.3	114.2
23	h_c	588	607	608	630	298.5
24	G	408,000	408,000	408,000	407,000	140,900
25	V	2.35	2.35	2.35	2.34	0.817
26	$\left(\frac{\mu_w}{\mu_a}\right)^{0.14}$	0.910	0.911	0.912	0.912	0.924
27	$\left(N_{Pr}\right)^{2/3}$	3.260	3.257	3.262	3,270	3.154
28	J	0.00690	0.00706	0.00716	0.00745	0.00975
29	N_{Re}	10,820	10,860	10,810	10,710	4,100
30	W_a	0	0.1577	0.463	1.258	0
31	Q_a	0	1.656	4.81	13.60	0
32	Air, percent	0	2.82	7.78	19.3	0

TABLE III.- SUMMARY OF DATA AND RESULTS; METHANOL WITH ENTRAINED AIR - Concluded

Item	Run	150A	150B
1	W_c	960	947
2	t_{ci}	101?1	98.8
3	t_{co}	124.7	124.0
4	q_c	14,310	15,060
5	W_s	15.70	17.24
6	P	27.1	26.9
7	t_s	244.6	244.1
8	h_{fg}	949.2	949.4
9	q_L	670	680
10	q	14,230	15,690
11	Deviation in heat balance		
	$(q_{sc} - q_c)(100)/q_{sc}$, percent	-0.6	-4.1
12	Temperatures		
	A-1	182.3	179.6
	A-2	180.5	178.0
	A-3	183.2	180.5
	A-4	184.3	181.4
	B-1	203.5	198.5
	B-2	204.6	201.2
	B-3	204.1	199.9
	B-4	204.8	200.5
	C-1	211.8	207.0
	C-2	213.8	209.8
	C-3	213.8	209.3
	C-4	214.5	210.0
	D-1	212.5	208.4
	D-2	214.7	210.2
	D-3	216.3	212.2
	D-4	212.5	208.0
13	t_w	203.6	199.7
14	q_{av}/A_o	28,940	31,200
15	Δt_w	2.60	2.80
16	$1/h_d$	.	
17	Δt_d		
18	t_{li}	201.0	196.9
19	$t_{li}(top)$	211.4	206.9
20	P_l	24.4	25.3
21	t_{bp}	172.7	174.6
22	t_{ca}	112.9	111.4
23	h_c	323.6	359.0
24	G	141,800	139,800
25	V	0.821	0.810
26	$\left(\dfrac{\mu_w}{\mu_a}\right)^{0.14}$	0.925	0.927
27	$(N_{Pr})^{2/3}$	3.165	3.178
28	j	0.01059	0.01202
29	N_{Re}	4,080	3,992
30	W_a	0.0832	0.2892
31	Q_a	0.974	3.19
32	Air, percent	4.64	13.92

TABLE IV.- PHYSICAL PROPERTIES OF METHANOL

Temperature		μ	C	k	$\left(N_{Pr}\right)^{2/3}$	ρ	H	p
($^{\circ}$C)	($^{\circ}$F)							
0	32	1.955	0.559	0.1307	4.120	50.58	0.00	0.56
10	50	1.670	.575	.1270	3.852	49.99	10.24	1.06
20	68	1.438	.590	.1234	3.614	49.40	20.72	1.85
30	86	1.246	.605	.1197	3.411	48.81	31.47	3.13
40	104	1.088	.622	.1161	3.240	48.23	42.52	5.09
50	122	0.957	.640	.1125	3.095	47.64	53.90	7.94
60	140	.845	.660	.1088	2.973	47.05	65.63	12.23
70	158	.752	.683	.1052	2.878	46.46	77.74	18.15
80	176	.674	.707	.1015	2.804	45.87	90.26	26.04
90	194	.607	.731	.0979	2.740	45.29	110.20	36.68
100	212	.549	.757	.0943	2.689	44.70	116.60	50.60
110	230							69.20

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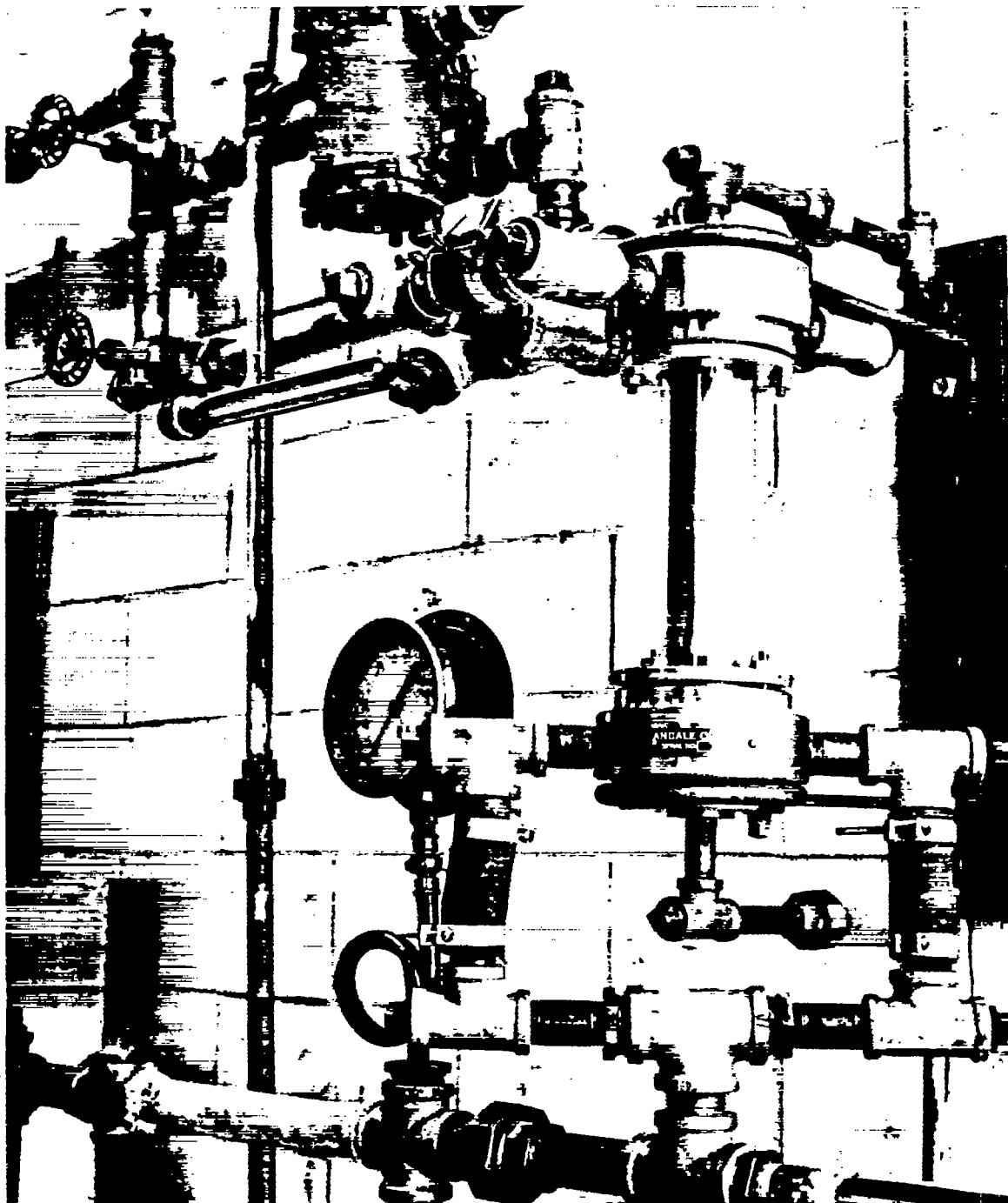
Figure 1.- Heat exchanger (unlagged).
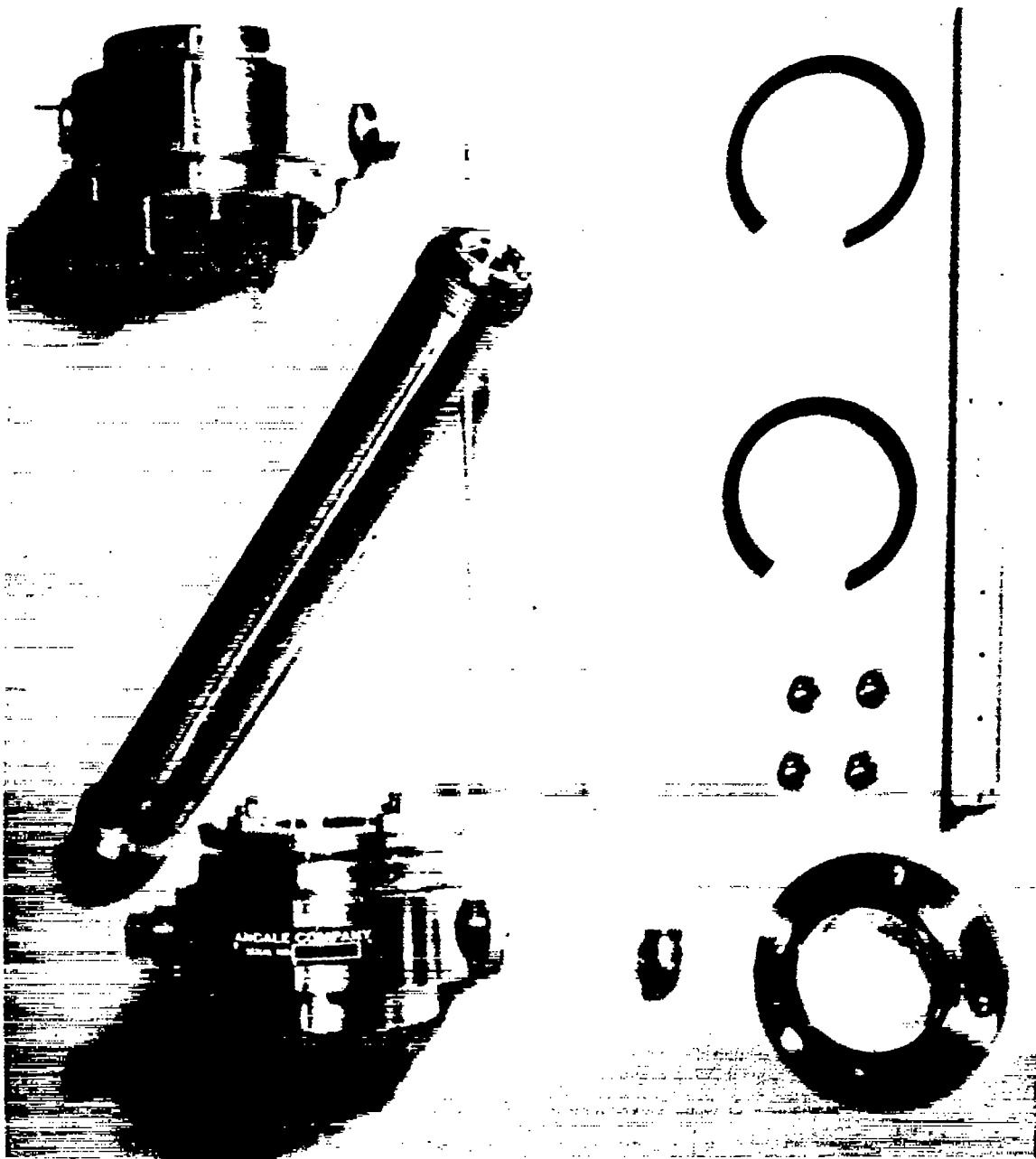
Figure 2.- Heat exchanger (disassembled).
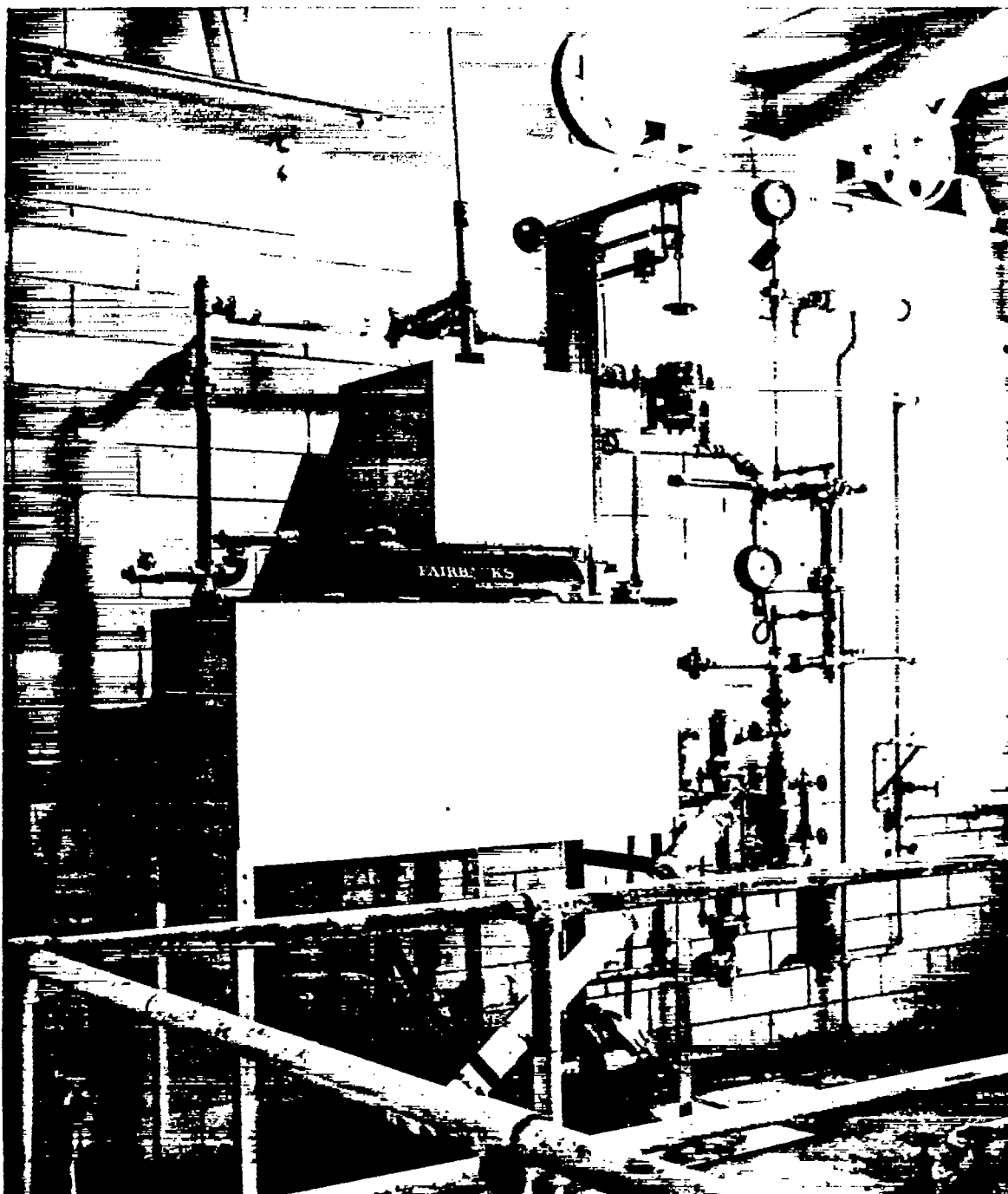
Figure 3.- View of test rig (unlagged).
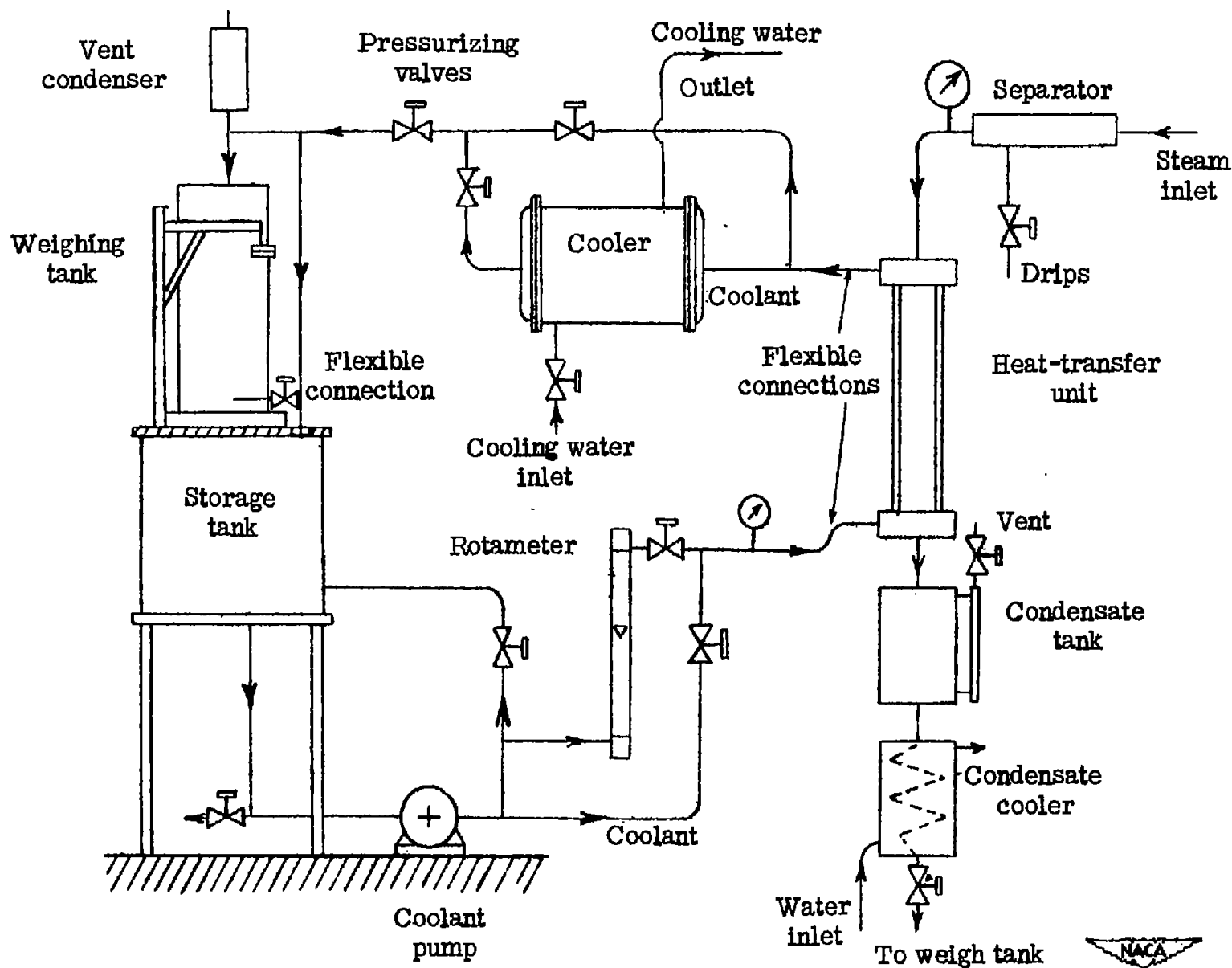
Figure 4.- Diagrammatic layout of apparatus.
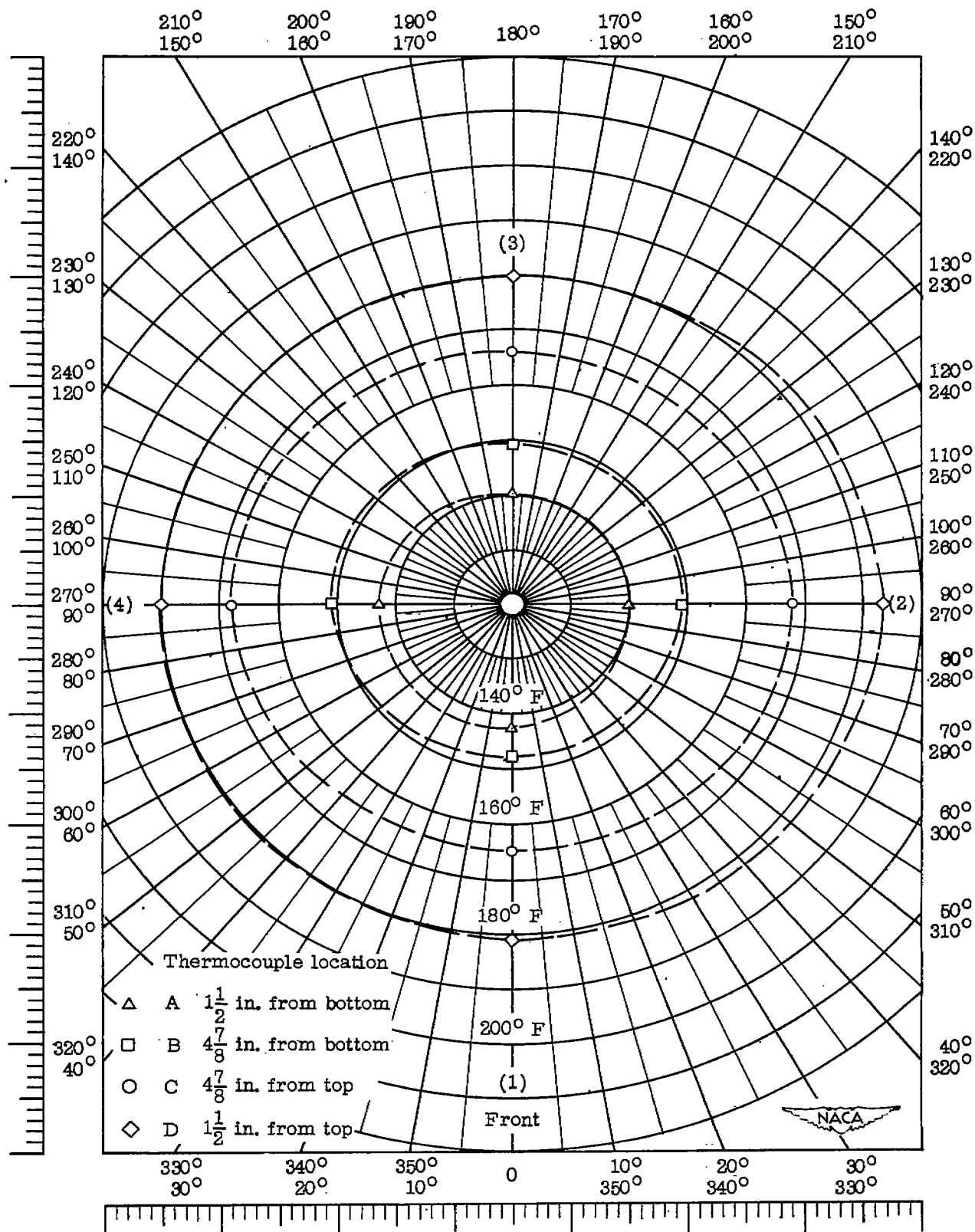
Figure 5.- Tube-wall temperature distribution. Data for run 59.
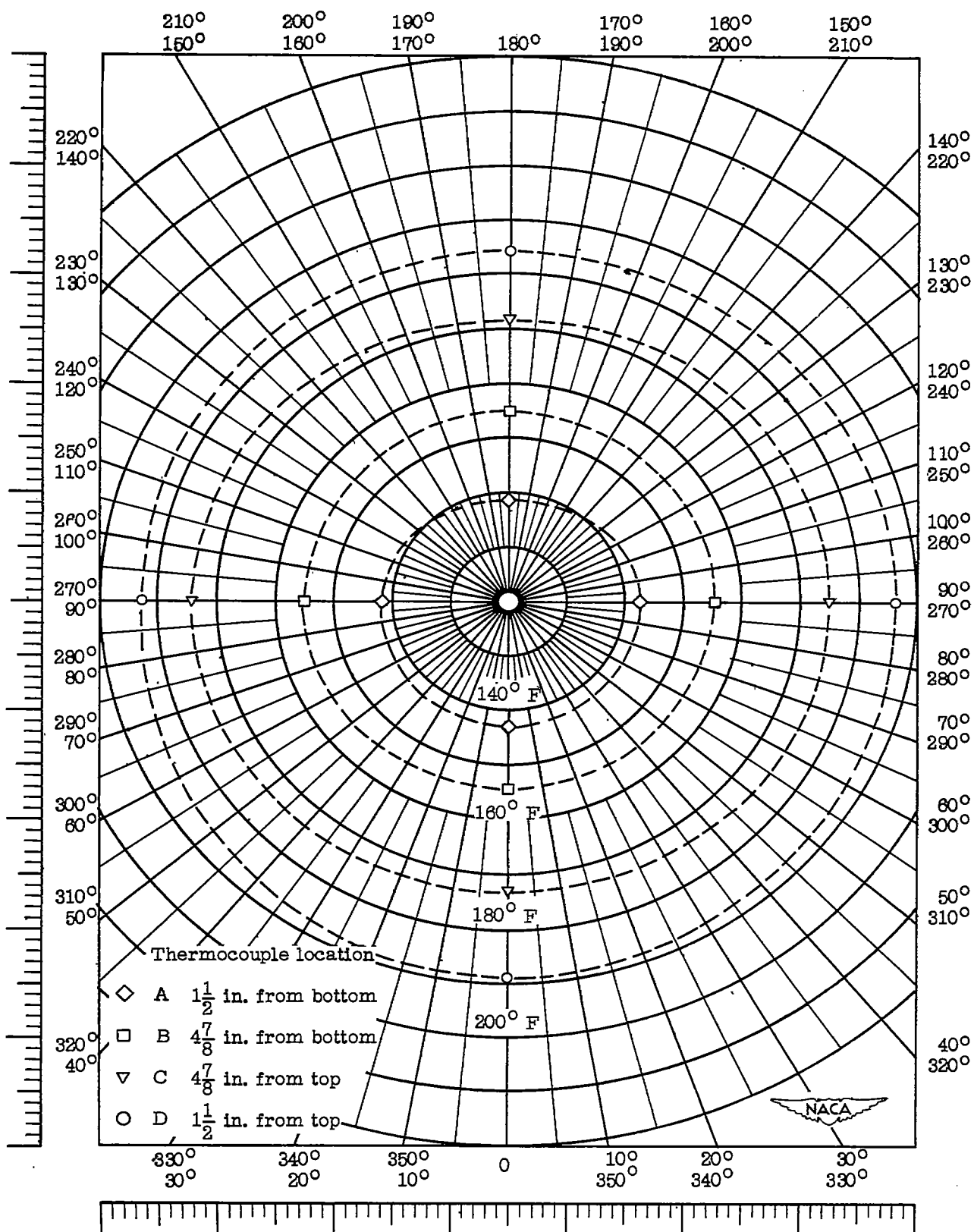
Figure 6.- Tube-wall temperature distribution. Data for run 93.
Coolant, menthol.
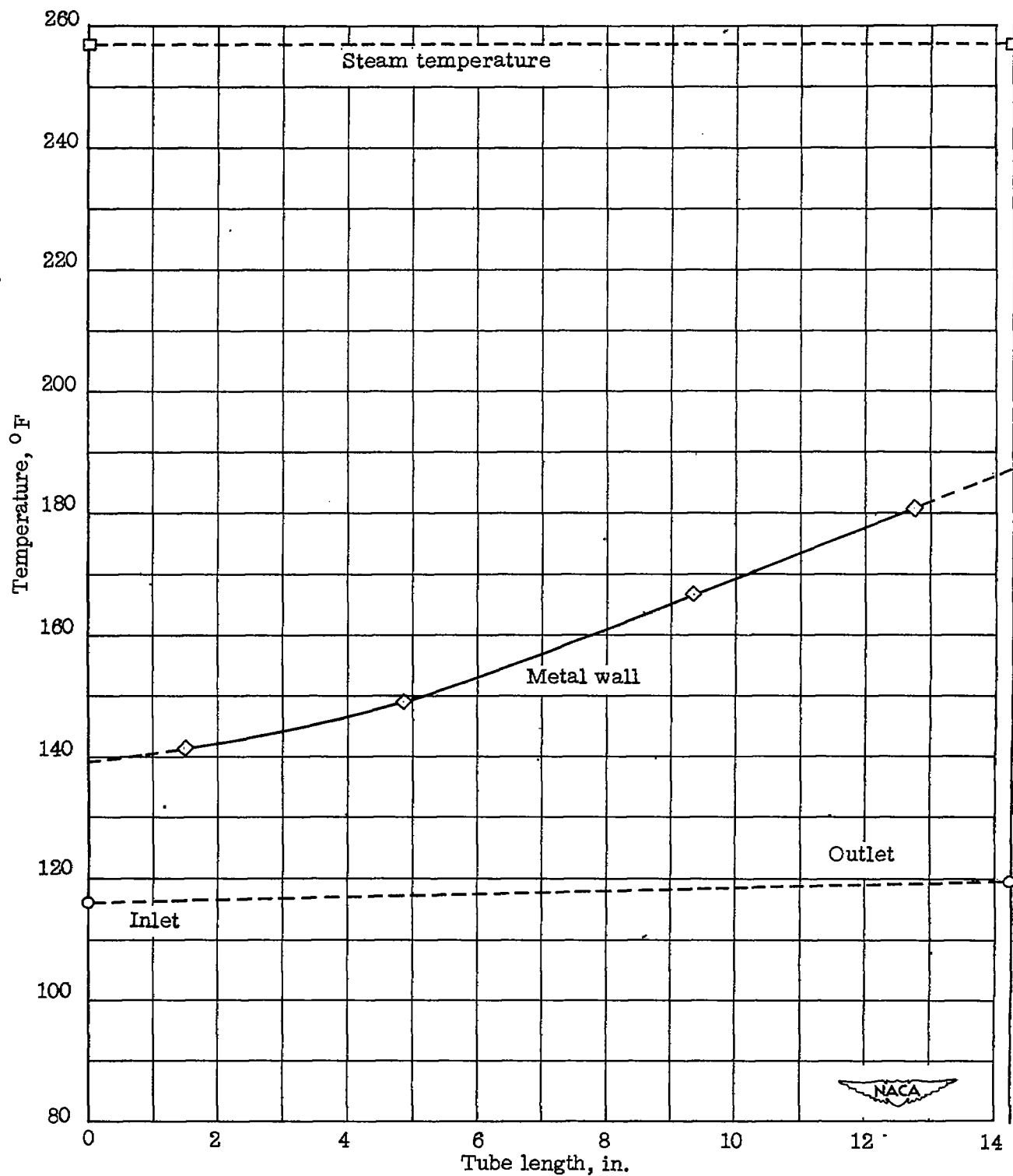
Figure 7.-   Temperature distribution against tube length.   Run 59.
Coolant, water.
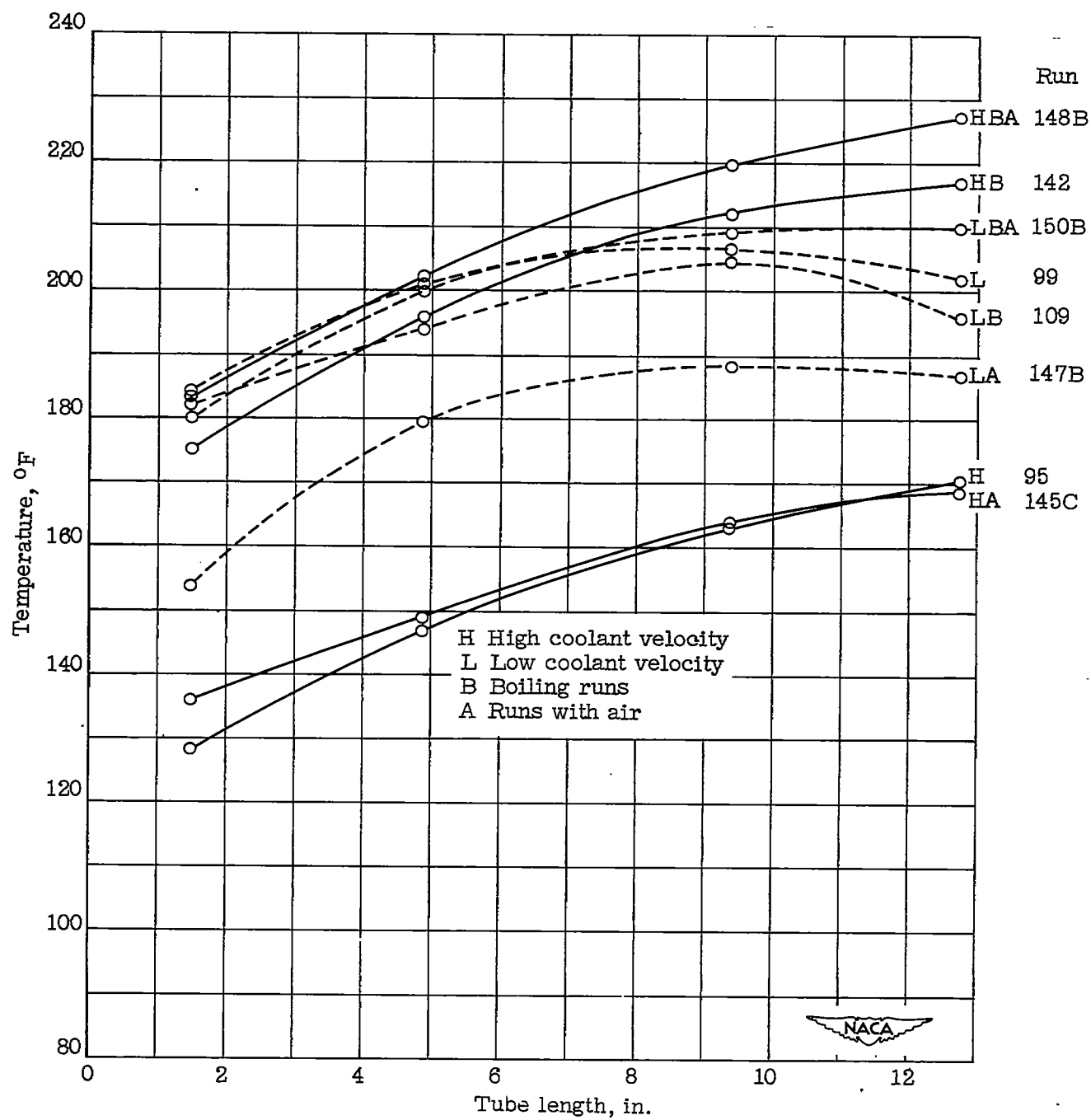
Figure 8.- Longitudinal temperature distribution for various typical runs.
Coolant, methanol.

$$j = 1.86\left(\frac{D_e G}{\mu}\right)^{-2/3}\left(\frac{L}{D_1 + D_2}\right)^{-1/3}$$

○ Water
△ Methanol

$$j = 0.027\left(\frac{D_e G}{\mu}\right)^{-0.2}$$

$$j = 0.023\left(\frac{D_e G}{\mu}\right)^{-0.2}$$
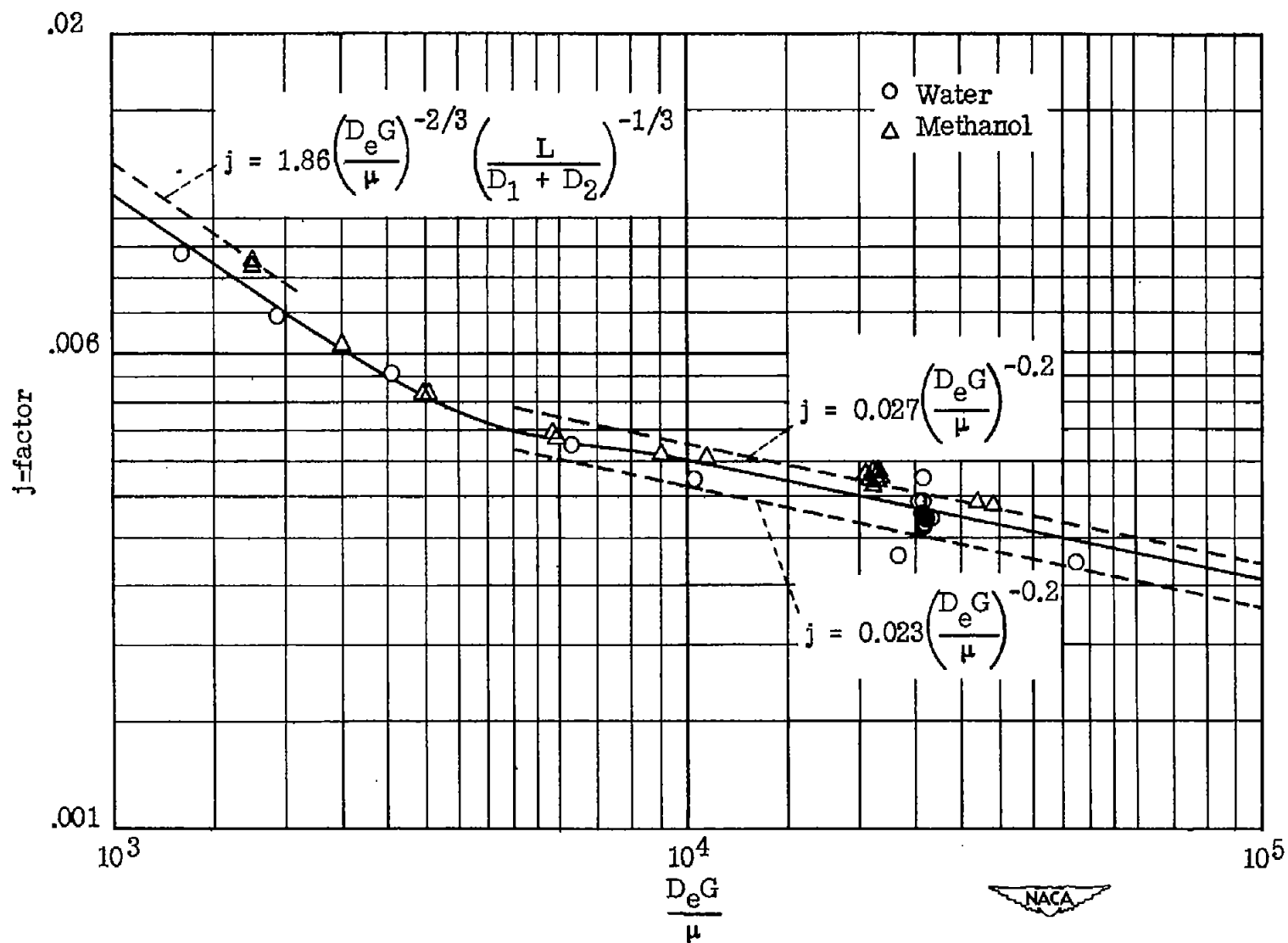
Figure 9.- j-factor against Reynolds number. Nonboiling data.
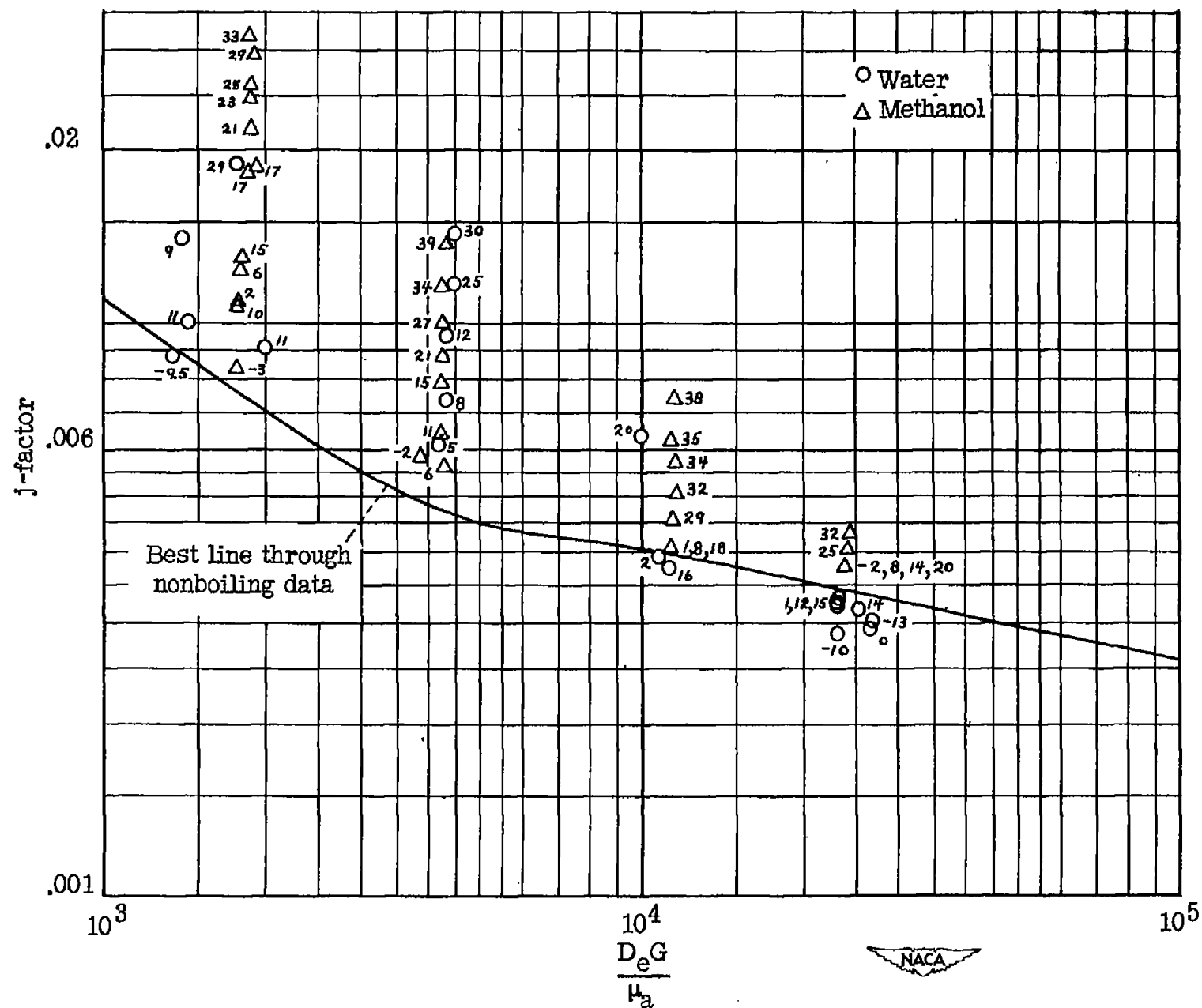
Figure 10.- j-factor against Reynolds number. Boiling data. Numbers denote $\left(t_{li} - t_{bp}\right)$.
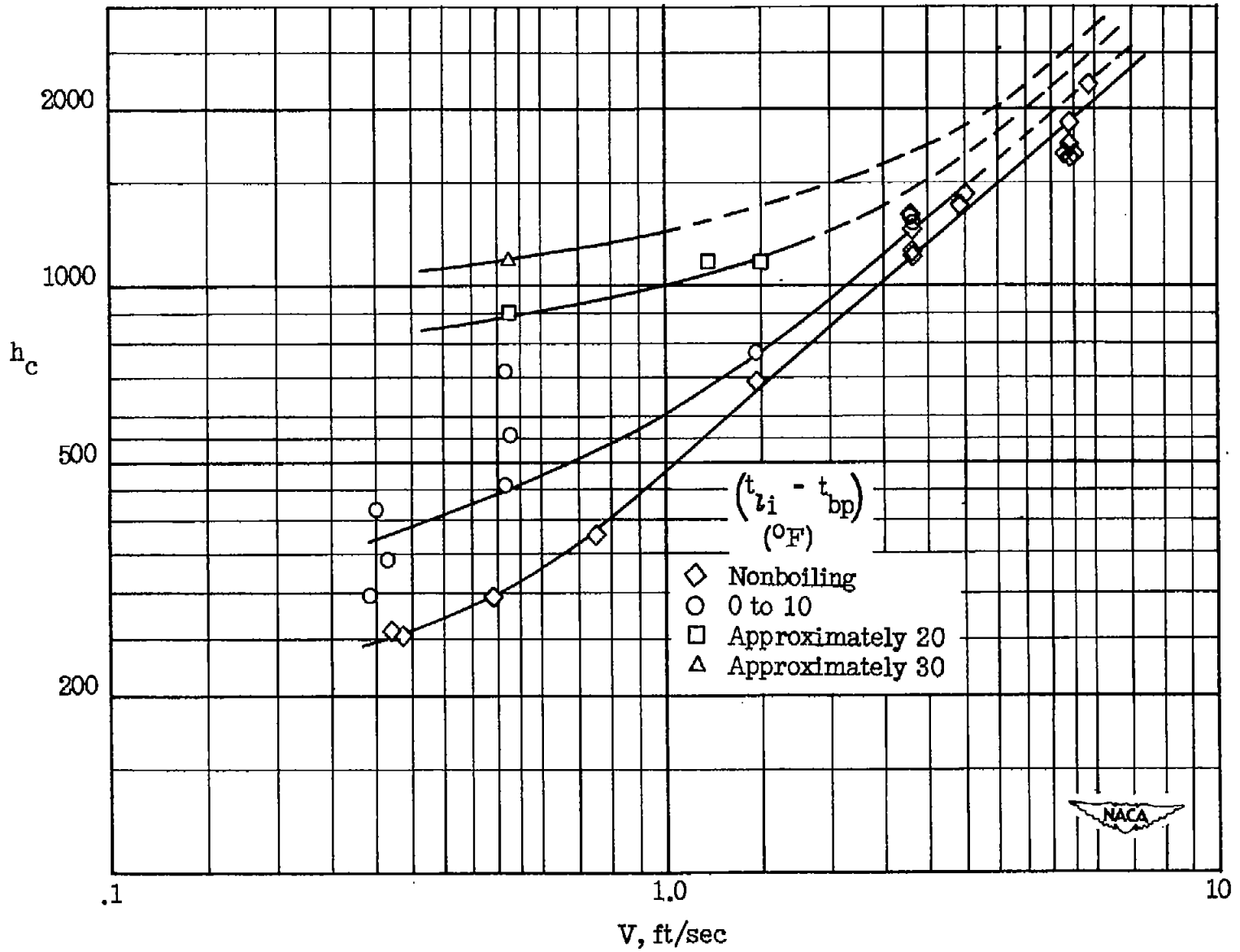
Figure 11.- Heat-transfer coefficient against coolant velocity for water.
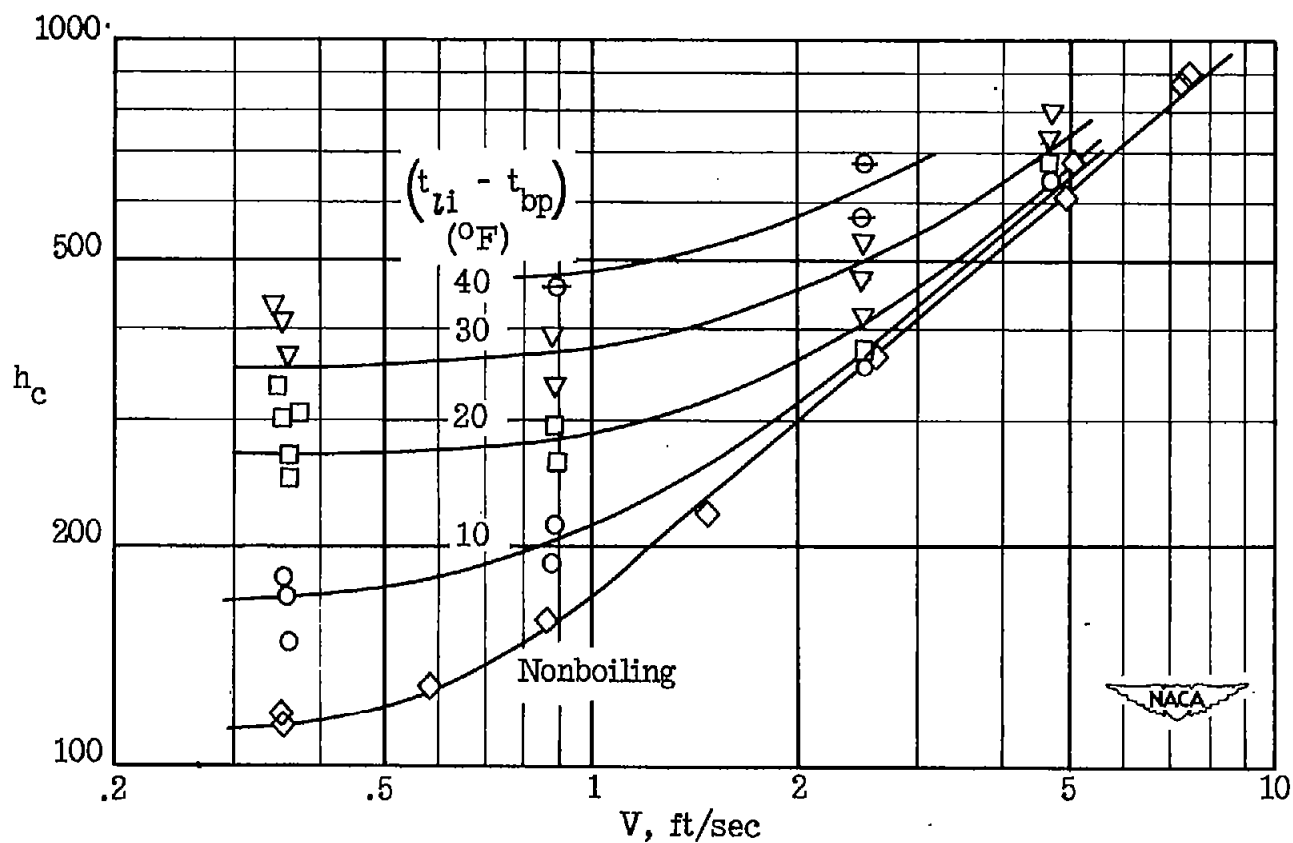
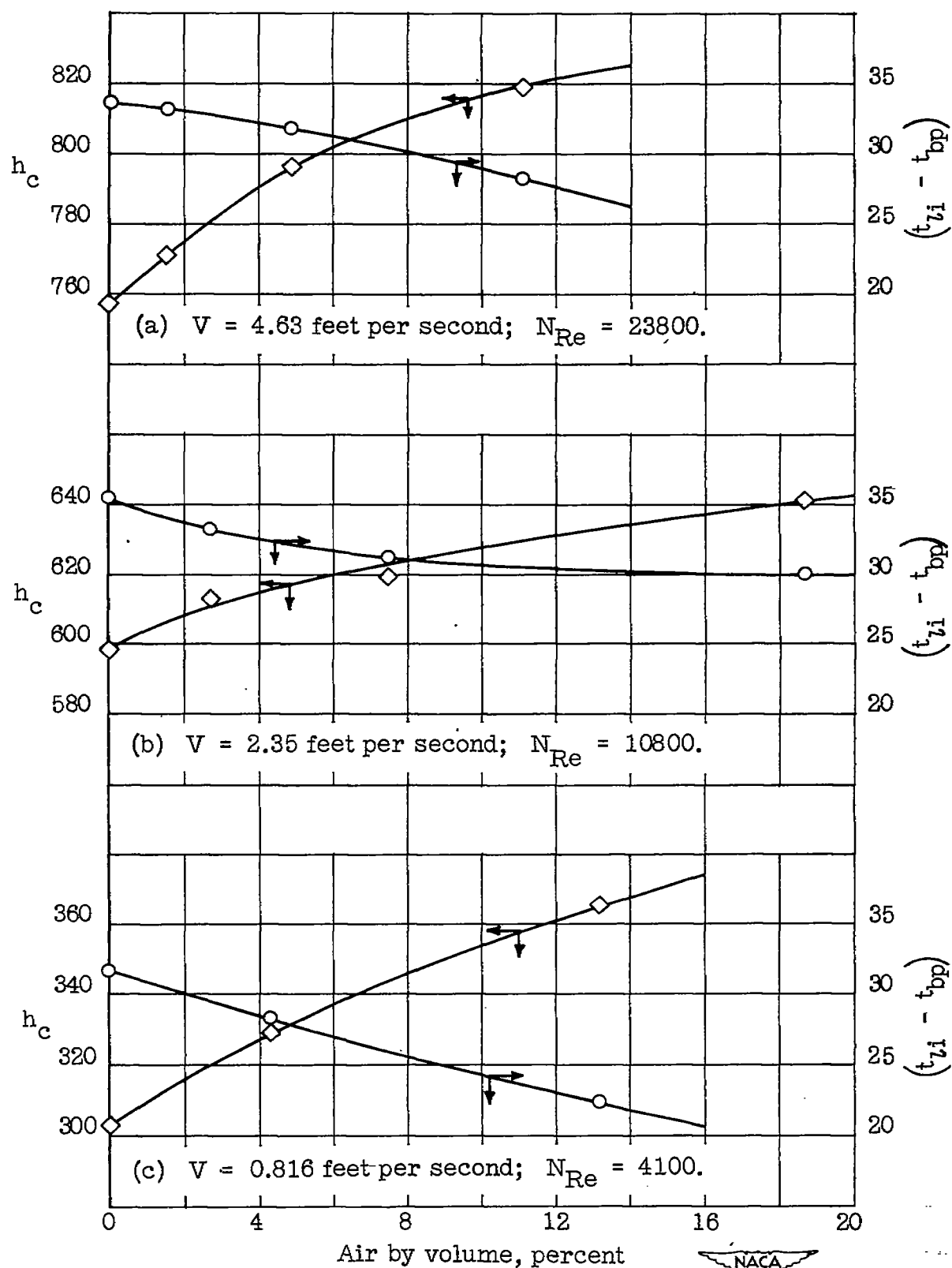Figure 12.- Heat-transfer coefficients between cylinder and methanol as functions of coolant velocity. Effect of $\left(t_{li} - t_{bp}\right)$ for runs without air.
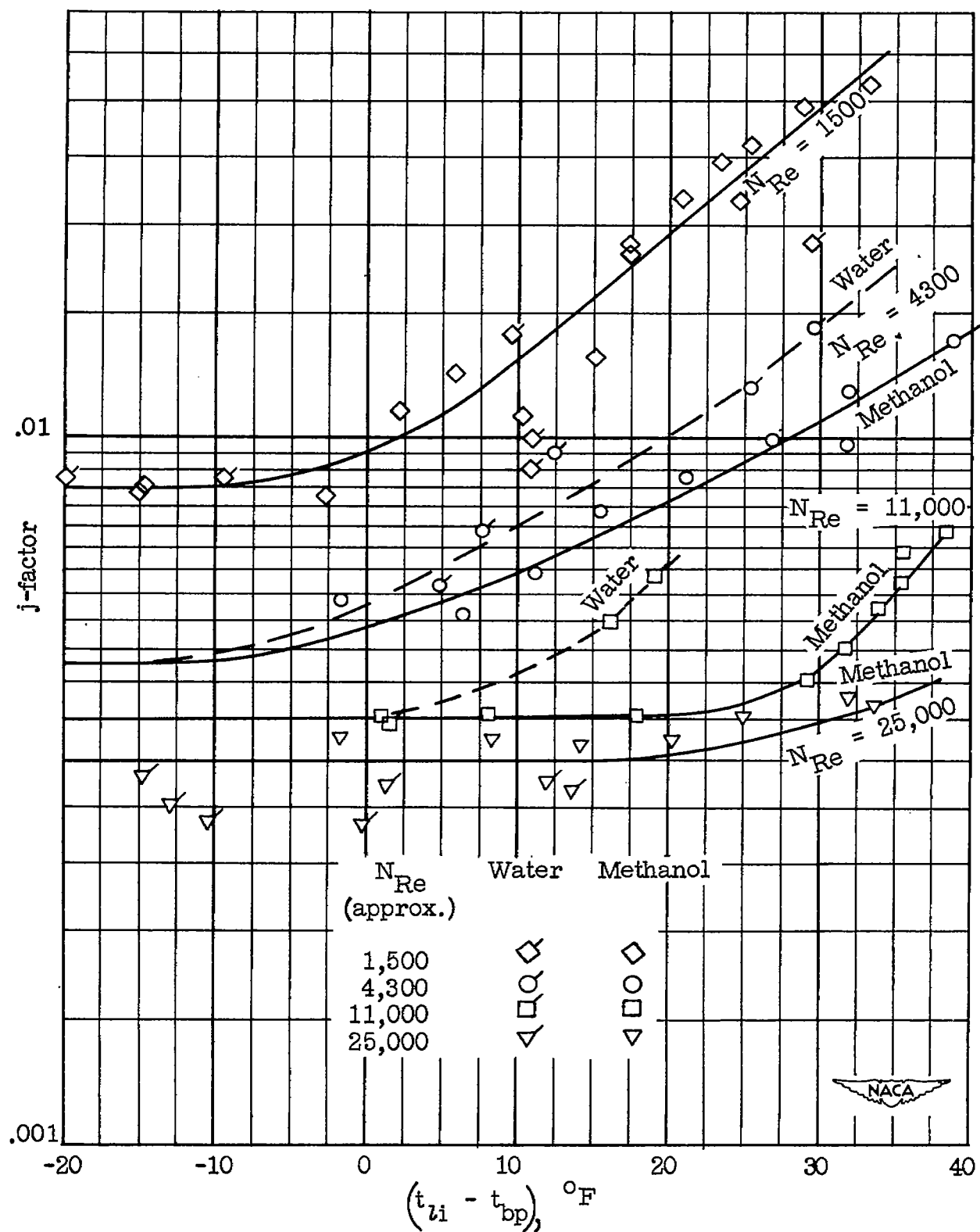
Figure 13.- j-factor against average temperature excess. Horizontal
part at beginning of each curve corresponds to nonboiling value.
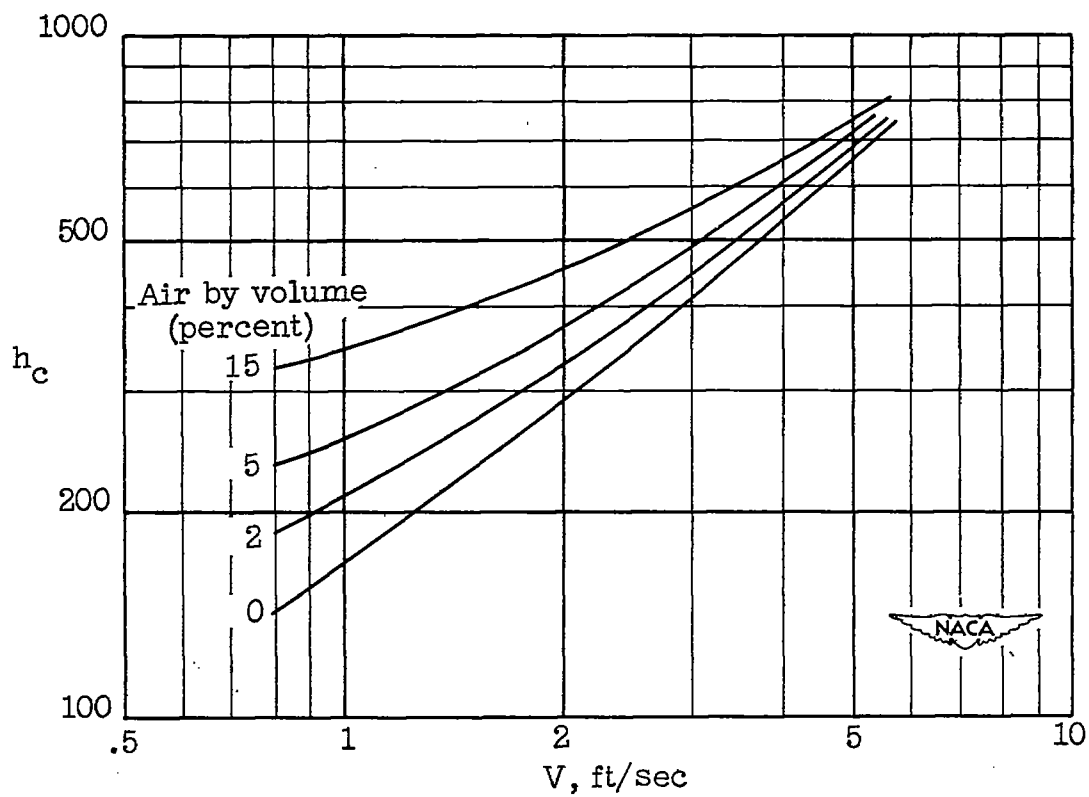
Figure 14.- Heat-transfer coefficient between cylinder and methanol as functions of coolant velocity. Effect of percent entrained air.

(a)   V = 4.63 feet per second; N_{Re} = 23800.

(b)   V = 2.35 feet per second; N_{Re} = 10800.

(c)   V = 0.816 feet per second; N_{Re} = 4100.

Air by volume, percent

Figure 15.-   Effect of percent of air by volume in heat exchanger for various series of boiling runs.   Coolant, methanol.
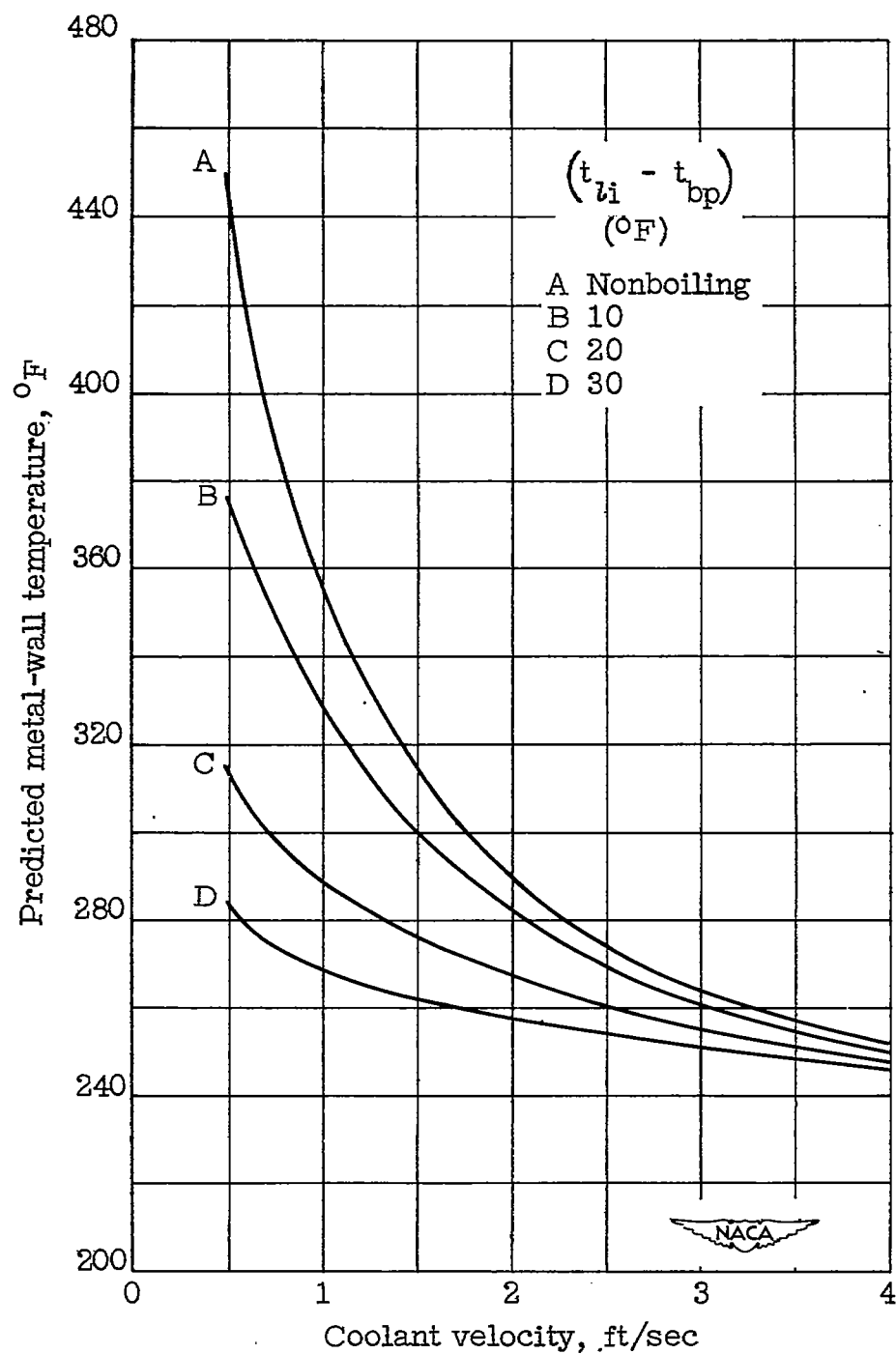
Figure 16.- Predicted metal temperature against coolant velocity. Heat flux, 100,000 Btu/(hr)(sq ft); temperature, 190° F; coolant, water.
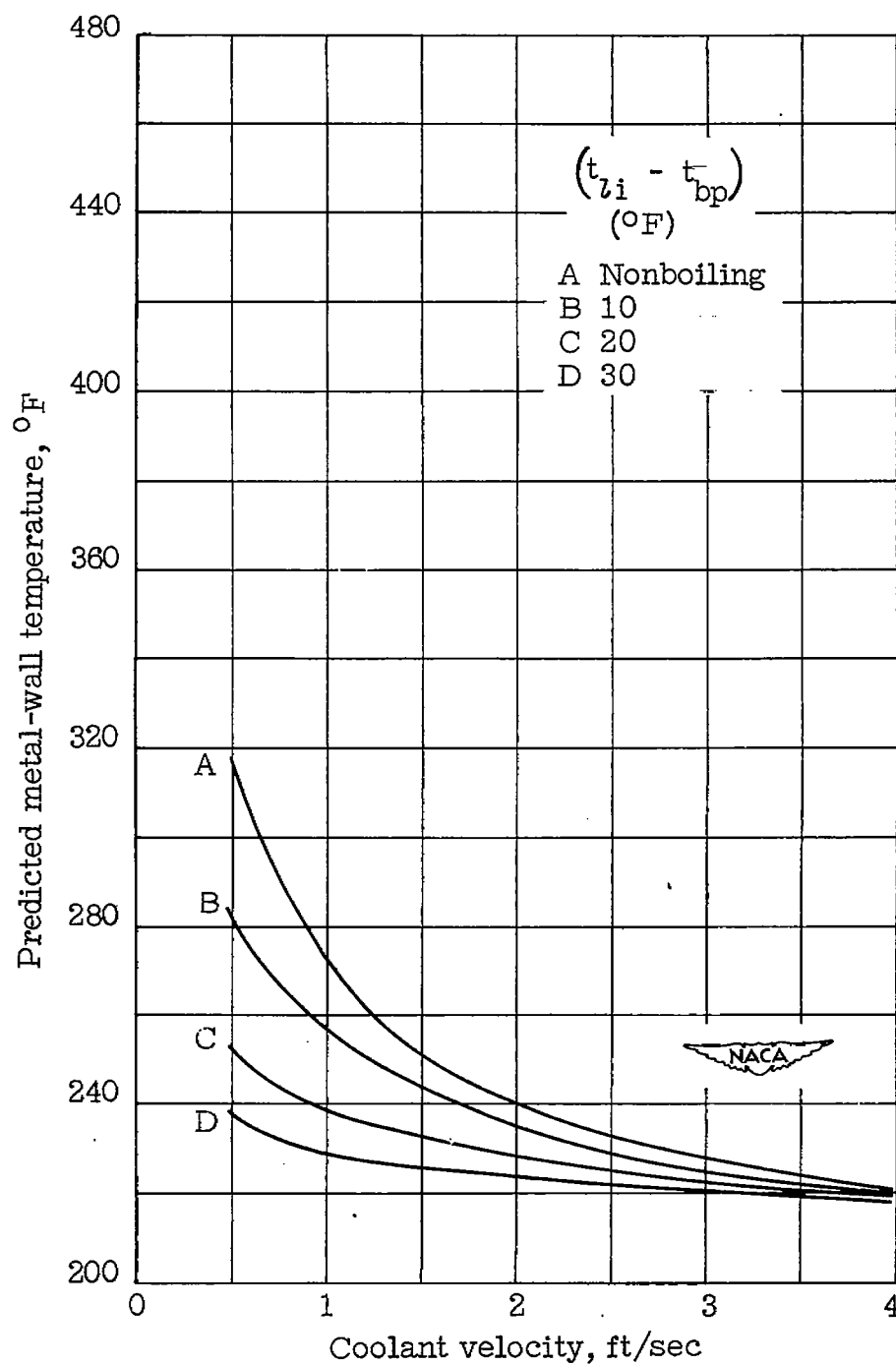
Figure 17.- Predicted metal temperature against coolant velocity.
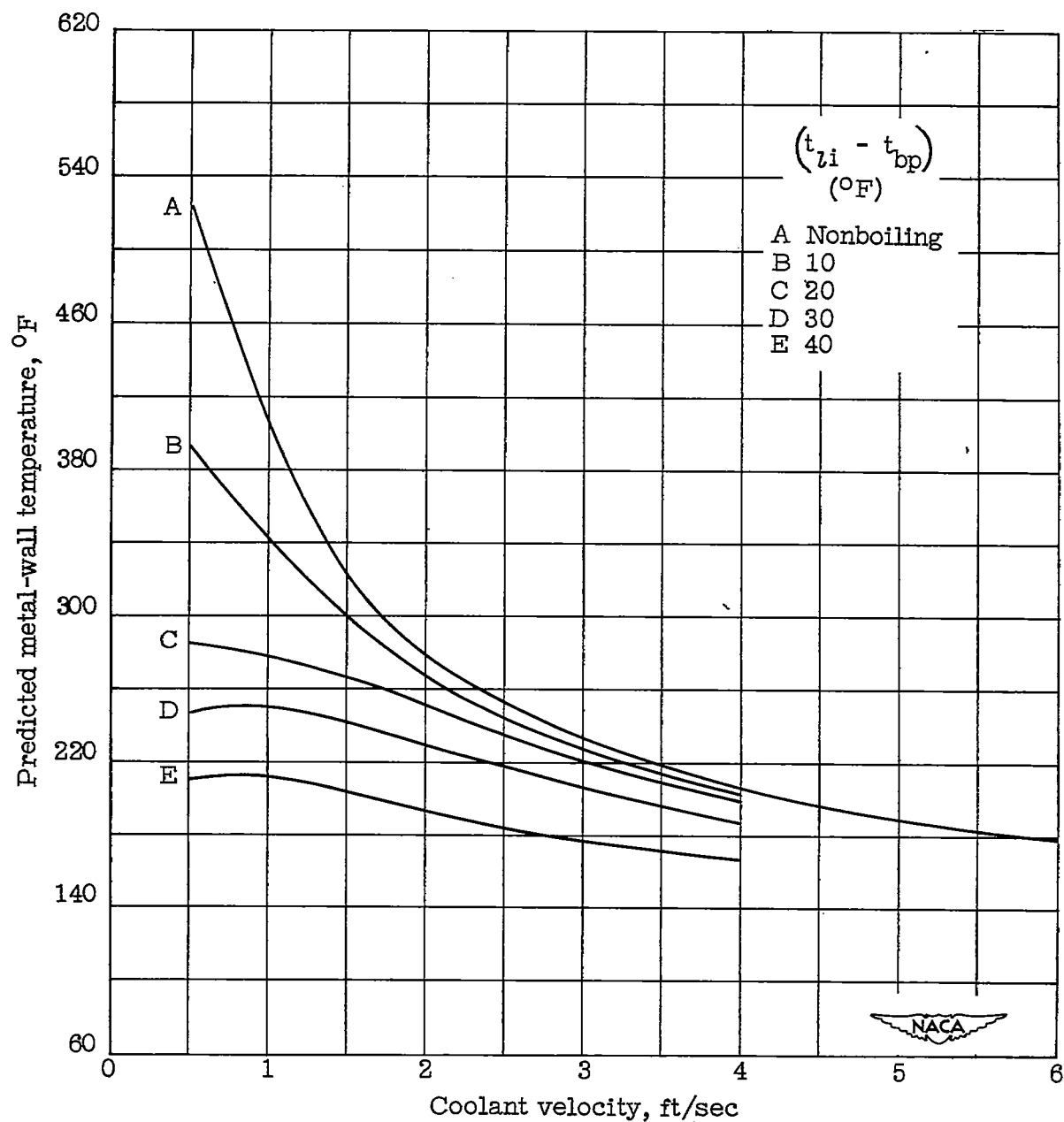Heat flux, 50,000 Btu/(hr)(sq ft); temperature, 190° F; coolant,
water.

Figure 18.- Predicted metal-wall temperature against coolant velocity. Heat flux, 50,000 Btu/(hr)(sq ft); temperature, 110° F; coolant, methanol (no air).